DEPARTMENT OF CIVIL ENGINEERING AND THE BUILT ENVIRONMENT

Surface Treatments for RC Structures in Marine Environments: A Literature Review

A research report for the partial fulfilment of the requirements for the degree of

MASTER OF ENGINEERING

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Acknowledgements

In the name of God, the Most Gracious and the Most Merciful.

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Abstract

If designed correctly, structures made from reinforced concrete have the potential to be very durable and are capable of enduring a wide variety of hostile environmental conditions. However, structural design and engineering standards that are currently available do not provide for sufficient and continuous durability compliance. As such, during the design phase, the long-term durability of concrete structures is often overlooked. Inadequate durability may result in premature deterioration and significant unforeseen repair costs. Many reinforced concrete structures worldwide are reaching their designed service life, and it is unlikely that they will be decommissioned and rebuilt, primarily due to financial difficulties. As a result, there is an amplified need to maintain and extend the service life of existing structures and ensure that all newly built structures last as long as possible.

The harsh marine environment that causes the steel reinforcement to corrode in a concrete structure is one of the primary causes of premature deterioration. Whilst patch repairing defective concrete is often the first step in correcting premature deterioration, it may not prove to be long-lasting, without the added use of surface treatment systems, especially in non-patch-repaired locations. Reinforcement corrosion in marine environments affects the durability of structures due to the high presence of chlorides and moisture availability. The chloride ions in seawater reduce the protective oxide coatings that form on the reinforcement, thereby inducing corrosion. With that being said, there is an increased demand for the application of surface treatment systems, as they provide reinforced concrete structures in marine environments with protection from deterioration related to the ingress of chloride and moisture.

This research critically examines the protective benefits of surface protection systems applied to reinforced concrete structures in marine environments. It focuses on the deterioration of reinforced concrete structures in marine environments and conducts a comprehensive and in-depth literature review of surface treatment systems. A particular focus is on the service life extension and the durability enhancement that these treatments have on concrete structures.

According to BS EN 1504, surface treatments can be classified into four types of surface protection systems: surface coatings, hydrophobic impregnations, impregnations or surface sealers, and screeds and overlays. Their function, types and uses, and performance in marine environments, are reviewed.

While the study demonstrated that all surface treatments protected reinforced concrete structures, the analysis of the literature showed that surface coatings, particularly polyurethane coatings, provided the best protection for reinforced concrete structures in marine environments. Studies have shown that these coatings can increase the service life of these structures by up to 7.8 times compared to untreated concrete.

A summary of the different surface treatment systems is discussed in detail in this dissertation. The summary includes the different types within a particular treatment system, the reason one would consider applying these systems, and a description of the benefits thereof. It may aid engineers and practitioners in selecting the correct treatment system for projects in marine environments.

Furthermore, this research appraises various international standards and the status of specifications concerning the advances in the field. As existing infrastructure is increasingly ageing, the need for repair and protection is rapidly growing. In addition, the substantial development of new materials and methods for repairing and protecting reinforced concrete structures has led to the need for revised standards.

Table of Contents

List of Figures

List of Tables

Abbreviations

ASTM	ASTM International (formerly; American Society for Testing and Materials)
BS	British Standard Code of Practice
BS EN	British Standard European Norm
EN	European Standards
ISO	International Organization for Standardization
OPC	Ordinary Portland cement
RC	Reinforced concrete
RILEM	International Union of Laboratories and Experts in Construction Materials, Systems and Structures
SANS	South African National Standards
UV	Ultraviolet
w/b	Water to binder ratio
w/c	Water to cement ratio

Glossary

Chloride ion concentration refers to the amount of chloride ions in a solution.

Concrete cover refers to the outer surface layer of concrete which protects the reinforcement from corrosion.

Diffusion is the process by which liquids, gases or ions move through a porous material under the action of a concentration gradient.

Durability is defined as the ability of a structure to withstand the conditions of service for which it was designed without significant deterioration.

Permeability is a measure of the amount of water, air and other substance that can enter the concrete matrix.

Porosity is used to define the proportion of the total volume of the concrete that is occupied with pores generally expressed as a percentage.

Service life is defined as the period of time in which a structure is capable of performing the function for which it was designed or constructed.

Sorptivity refers to the material’s ability to absorb and transmit water through it via capillary suction.

1. Introduction

1.1 Background

A structure that is considered durable should be able to withstand the design environment throughout its entire design life without the need for significant repairs while still maintaining serviceability (Owens, 2009; EN 1992-1-1). During the design stage, the fact that a structure's performance decreases with time due to deterioration is often overlooked. Unfortunately, structural design and engineering standards do not provide adequate and continuous durability compliance. Consequently, such compliance falls to the design engineer to address, who may not necessarily have the required skills and knowledge to carry out such functions. Inadequate durability could result in premature deterioration and significant unforeseen repair costs (Bijen, 2003).

In South Africa, many RC structures are reaching their designed service life. However, it is implausible that these structures will be decommissioned and rebuilt, given the lack of finances. As a result, there is an amplified need to maintain and extend existing structures' service life and ensure that all newly built structures last as long as possible (Bulbulia, 2021).

In harsh environments, notably in the marine environment, corrosion of reinforcing steel presents a severe threat to RC structures (Alexander, Beushausen & Otieno, 2012). Numerous methods are proposed to improve the durability of concrete structures in aggressive environments, including, but not limited to, the use of corrosion inhibitors, using low w/b high-performance concrete mixtures, using coated or stainless steel reinforcement, applying cathodic protection and using concrete surface treatments. Considering that the deterioration mechanisms are generally governed by the ingress of aggressive agents entering the concrete, the use of surface treatment systems is often seen as the most economical and prevalent selection by practitioners to enhance the corrosion resistance of RC structures in marine environments (Sadati, Arezoumandi & Shekarchi, 2015).

1.2 Research Problem

Surface treatment systems are becoming increasingly popular to preserve the vast number of existing concrete infrastructure that has deteriorated and to protect both new and existing structures from the ingress of aggressive agents and the associated damage (Mays, 2003). Engineers and concrete practitioners have recognised a growing need to provide additional protection to RC structures exposed to harsh marine environments. As a result, various protection methods are adopted, the most common and the most effective being the use of protective surface treatments on concrete (Almusallam et al., 2003). Taking the above into account, it has become imperative that specialised literature on surface treatment systems is made readily available.

There is a lack of guidelines for the selection of suitable surface treatment systems. Moreover, there is a growing need to understand the functions and mechanisms, the types and uses, the factors that influence the performance, and specifically the effectiveness of surface treatment systems in aggressive marine environments.

Previous literature has recognised that surface treatment systems increase the durability of RC structures. However, it has become apparent that there is a need to analyse and understand the extent to which such treatments perform, particularly in the marine environment over different periods.

1.3 Aim of the Research

This study aims to provide a detailed assessment of available surface treatment systems, specifically concentrating on the treatment systems for RC structures in the marine environment. This study also intends to serve as a guideline to aid engineers and practitioners in selecting suitable surface treatment systems.

1.4 Objectives

This study will focus on the following objectives:

1. To assess and analyse the literature on laboratory and in-situ performance of protective surface treatment systems with a focus on RC structures in marine environments, which includes:
    - The functions and mechanisms;
    - The types;
    - The factors that influence the performance; and
    - The effectiveness of surface treatment systems.
2. To provide a summary of the findings in tabular format, which may aid engineers and practitioners in selecting a surface treatment type.
3. To appraise the availability of the various international standards and their current developments.

1.5 Research Questions

The main questions for this research study emanating from the objectives are indicated below:

- What are the dominant deterioration mechanisms involved in RC structures in marine conditions?
- Which surface treatments are considered to be effective in marine environments?
- What are the specific characteristics required of surface treatments?
- How do the surface treatments perform over time?
- Does the application method significantly affect the surface treatment's effectiveness and service life?

- What impact does the condition of the RC structure (for example, cracks, delamination and spalling) have on surface treatment application and performance?
- Which relevant and appropriate engineering standards provide guidelines for the application of different surface treatments?

1.6 Scope and Limitations

This report is restricted to a comprehensive desktop literature review of concrete surface treatment systems on RC structures in the marine environment, with the view of preparing a comparison of existing studies conducted on the performances of in-situ and laboratory surface protective treatment systems over different periods. This study is limited to the surface treatments' functions and mechanisms, their types, the factors that influence their performance, and the effectiveness and service life enhancement through surface treatment systems. It should be acknowledged that as this report forms part of an MEng dissertation, the details discussed herewith are considerably more complex than described in this report. Furthermore, the costs of the various surface treatments are not considered herein.

The following main tasks were undertaken during this research:

- Reviewing research papers, textbooks, manufacturer's guidelines and engineering standards available on the topic to undertake a comprehensive literature review.
- Analyse and synthesize the information gathered as described above, and align it with the research objectives listed hereinabove.
- Report on all findings in this dissertation.

It should be noted that the author carried out no sampling or laboratory testing.

1.7 Outline of the Report Structure

This report is divided into six chapters.

Chapter 1 introduces the proposed study and provides a background to the problem whilst also motivating the significance of the research. Below is an overview of the chapters to follow:

Chapters 2 and 3 provide the subject theory by presenting a comprehensive literature review.

Chapter 4 appraises the performance requirements set out by various standards and guidelines.

Chapters 5 and 6 provide a conclusion and recommendations and a reference list, respectively.

2. Deterioration of RC Structures in Marine Environments

2.1 Introduction and Background

Structures made from reinforced concrete have the potential to be very durable. They can endure hostile environmental conditions if the concrete is adequately designed and accurately made and placed (Ahmad, 2003). Unfortunately, in practice, this durability requirement is not always achieved, which typically gives rise to premature reinforcement corrosion that causes structures to fail (Ha-Won Song & Velu Saraswathy, 2007). Deterioration may result from several factors, including the design, the materials used, the poor workmanship, the environmental influences during construction and the service life, as well as the loads acting on the structure. Many researchers have also attributed the premature deterioration of RC structures to the incorrect evaluation of the severity of their service environment (Almusallam et al., 2003).

There is a common misconception that there is no need for regular maintenance after constructing RC structures. However, without routine maintenance, expensive intervention and repairs are likely to be required, and the service life of RC structures could be significantly reduced (Meier & Wittmann, 2011).

The durability of a structure is defined as its ability to withstand the design environmental conditions over the design life without the need for significant repair or loss of serviceability. According to Owens (2009), concrete that is not very durable allows gasses and ions to move through the concrete’s microstructure. This allows deterioration mechanisms such as carbonation and chloride ingress to take place relatively easily.

This chapter describes the main deterioration mechanism that is observed in RC structures in marine environments. It further discusses the various transport processes involved.

2.2 RC Structures in the Marine Environment

In marine environments, reinforcement corrosion is one of the main deterioration mechanisms that affect the durability of RC structures due to the high chloride concentrations and moisture availability in the exposed environment (Mackechnie, 2001). RC structures in marine environments can be divided into different categories, i.e. submerged RC structures, RC structures in the tidal zone and RC structures in the vicinity of the sea. (Meira et al., 2010; de Medeiros et al., 2016) state that the aggressiveness of the chloride attack is directly influenced by the distance of the RC structures in relation to the ocean, as there is a lower intensity of chloride concentrations in the atmosphere further away from the sea. Costa & Appleton (2002) further added that cycles of wetting and drying, as with RC structures in the tidal zone, escalate the speed of chloride contamination. In these very aggressive exposure conditions, corrosion rates as high as 500 µm/year were measured.

The chloride ions in ocean water reduce the protective oxide layer that forms on the reinforcing steel surface. Once this ferric oxide layer is disrupted, corrosion of the reinforcement is possible, provided sufficient moisture and oxygen are available (Mackechnie, 2001).

Reinforcement corrosion is commonly observed by the cracking and spalling of the concrete cover due to the formation of expansive corrosion products and local pitting, which reduces the cross-sectional reinforcement area in a localized area (Mackechnie, 2001). If left unabated, deterioration may accelerate the RC structure's ageing, leading to severe cracking, delamination and spalling of the concrete.

2.2.1 Mechanism of corrosion of steel reinforcement in concrete

Reinforcement corrosion in concrete is mainly linked to chloride penetration into the concrete or carbonation of the concrete. These two phenomena cause the reinforcement to become thermodynamically unstable, i.e., de-passivated. The pore solution naturally protects steel embedded in concrete against corrosion. The cement pore solution has a pH of greater than 12.5, resulting in the formation of a very thin ferric oxide film (1-10nm thick) on the steel surface. This passive layer can be disturbed by chloride ingress or by the reduction in the alkalinity of the concrete. Once the passive layer is broken, the reinforcement becomes thermodynamically unstable and may corrode. For corrosion to occur, moisture and oxygen must be present at the cathode (Alexander, Beushausen & Otieno, 2012).

During the reinforcement concrete corrosion process, the iron is oxidized at the anode and oxygen is reduced at the cathode. In reinforced concrete, the steel acts as the metallic path between the cathode and the anode, and the alkaline pore solution is the electrolyte. The electrochemical reactions that describe the reinforcement corrosion process are shown in equations 2.1 and 2.2 below, while the schematic illustration of the corrosion process is displayed in Figure 2-1 below (Ahmad, 2003).

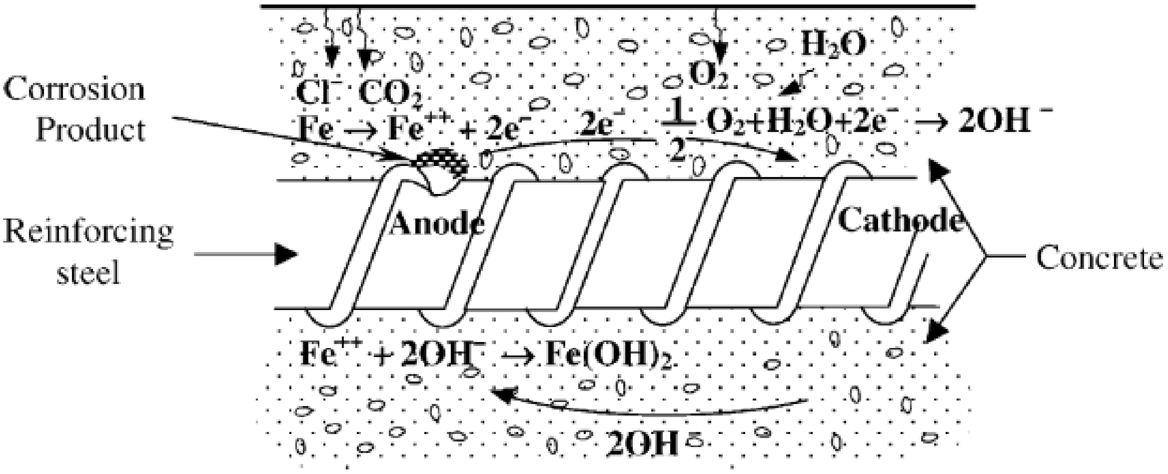


Figure 2-1: Illustration of the corrosion of reinforcement in concrete (Ahmad, 2003)

The corrosion reactions are as follows:

Anodic reaction: $Fe \rightarrow Fe^{2+} + 2e^{-}$ (2.1)

Cathodic reaction: $O_2 + 2H_2O + 4e^{-} \rightarrow 4OH^{-}$ (2.2)

Angst (2018) explains that the ingress of chlorides can activate corrosion due to exposure to ocean water or road de-icing salts. A minimum concentration of chlorides at the reinforcement, known as the threshold level, is required to disrupt the protective layer of ferric oxide film that forms under normal alkaline conditions. The activation of corrosion occurs at chloride levels of 0.4 % – 0.5 % by mass of cement. After the steel de-passivation, the corrosion rate is dependent on micro-effects such as the availability of water and oxygen (Mackechnie, 2001).

2.2.2 Three-stage corrosion damage model

While Tuutti (1982) explains that in the marine environment, the service life of an RC structure consists of only two stages (the initiation and propagation stages), Heckroodt (2002) further breaks the corrosion damage model of deterioration into three stages (the initiation, propagation and acceleration stages).

Figure ***2-2*** below displays the three-stage corrosion damage model.

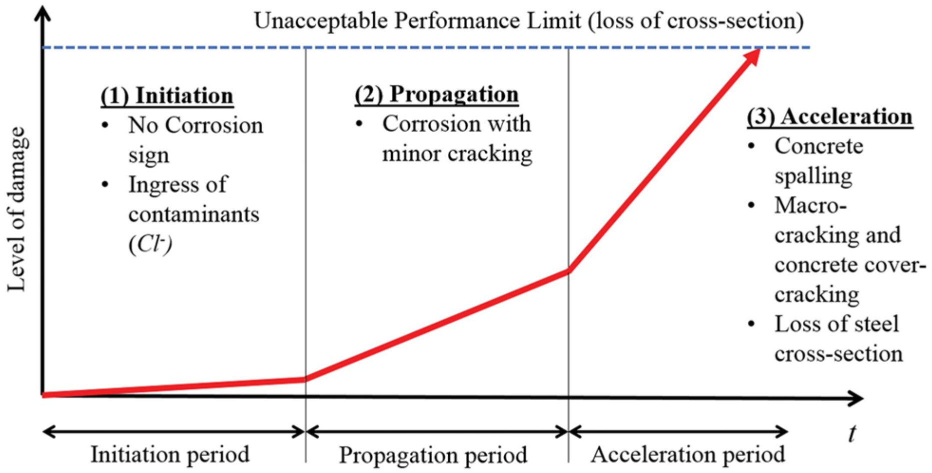


Figure 2-2: Three-stage corrosion damage model (Heckroodt, 2002)

a) Initiation period

The initiation period is the stage before corrosion begins. In this period, little or no damage occurs. During this stage, the ingress of damaging substances, such as chlorides and carbon dioxide, occurs. If chloride ions from the environment penetrate the concrete and reach the reinforcement, the protective passive layer may be locally destroyed (Loreto et al., 2011). Similarly, carbonation commences at the surface of the concrete and moves gradually towards the reinforcement. The alkaline concrete becomes neutralised by the carbon dioxide in the atmosphere. The pH of the pore liquid of the concrete decreases to approximately 9; at this stage, the passive layer is no longer stable (Loreto et al., 2011).

The quality of the concrete, i.e., permeability, pore solution chemistry, environmental exposure conditions, and cover depth, play a pivotal role in the rate of ingress of these harmful substances that may eventually cause reinforcement corrosion (Alexander, Beushausen & Otieno, 2012).

b) Propagation period

The breakdown of the passive or protective layer is a prerequisite for reinforcement corrosion to occur. After the corrosion activation phase, cracks occur as expansive corrosion products are generated. Corrosion rates can vary considerably depending on humidity and temperature. Most often, chloride ingress causes localised breakdown, while carbonation of concrete leads to the complete dissolution of the protective layer (Loreto et al., 2011).

c) Acceleration period

In this stage, the corrosion rate rapidly increases due to easy access to moisture, oxygen and aggressive agents through cracks and spalls. The concrete cover may not fully serve its purpose of assisting in controlling corrosion where extensive cracking, delamination and spalling occur. The RC structure becomes vulnerable and at risk of severe damage and loss of reinforcement cross-section (Heckroodt, 2002).

2.2.3 Macrocell and microcell corrosion

Poursaee (2016) explains that reinforced concrete elements crack under working conditions. However, cracks are not considered structural defects if they do not reach a certain width. Reinforced concrete is, therefore, customarily designed to act in a cracked state. Corrosion typically starts either adjacent to the crack or directly in the crack.

Poursaee (2016) explains that reinforcement corrosion in concrete occurs in 2 ways: macrocell and microcell.

a) **Macrocell** – Anodes and cathodes are separated in areas along the reinforcement bar. This occurs in chloride-induced corrosion of concrete that has a low resistivity. Macrocell corrosion has a large cathode and a small anode which results in substantial localised corrosion (pitting corrosion), whereby significant cross-section reduction is found (Poursaee, 2016). A macrocell corrosion schematic is illustrated in Figure 2-3.

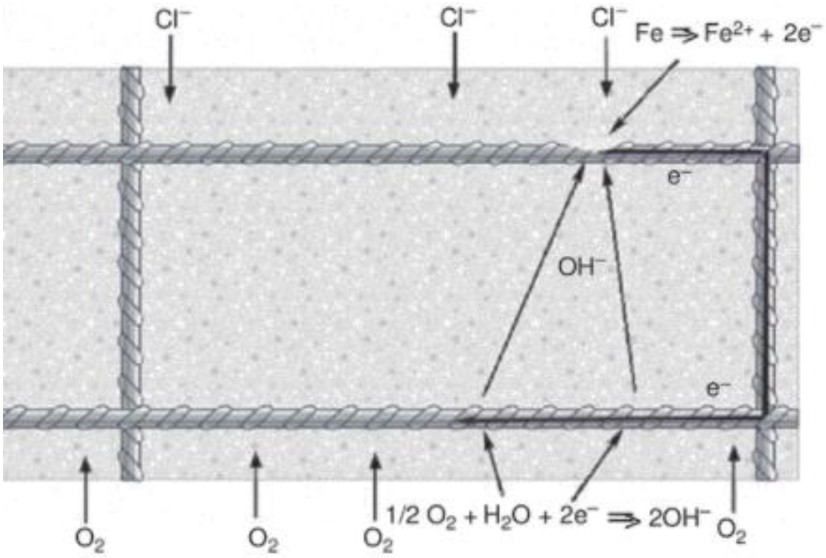


Figure 2-3: Schematic illustration of macrocell corrosion (Poursaee, 2016)

b) **Microcell** – This usually occurs in carbonation-induced concrete corrosion, where the anode and cathode sites are adjacent, with many cells along the reinforcement bar (Poursaee, 2016). A microcell corrosion schematic is illustrated in Figure 2-4.

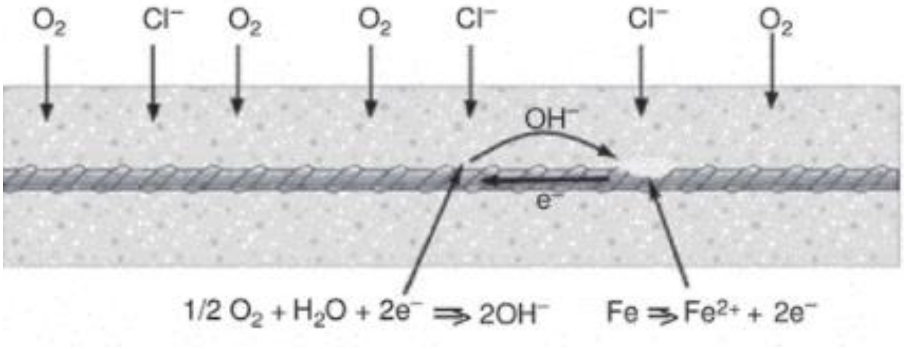


Figure 2-4: Schematic illustration of microcell corrosion (Poursaee, 2016)

2.2.4 Factors affecting the durability of concrete in marine environments

The deterioration of RC structures in marine environments is usually associated with external agents, such as chlorides penetrating the concrete cover and causing damage. The durability of the RC structure is thus crucial in protecting the RC structure from chloride ingress. Concrete durability is affected by several factors, including binder type, reinforcement depth, the severity of the RC structures' exposure and site practice (Mackechnie, 2001).

a) Binder type

The concrete type significantly influences reinforcement protection since the material affects the rate at which aggressive agents move through the concrete cover. Although the current codes make allowance for increased chloride resistance concrete, the binder types are, to a great extent, overlooked. In doing so, when considering the transport properties of concrete, the chemical effects are primarily ignored while the physical characteristics are recognised. Ingress largely depends on the reactions between the concrete material and the diffusant that reduces the concentration and compresses the pore structure. It has been proven that concrete containing slag and fly ash has significantly higher chloride binding properties, thus producing a higher chloride-resistant concrete (Mackechnie, 2001).

b) Cover to reinforcement

An RC structure's potential durability is greatly enhanced when sufficient concrete cover is provided. Under marine conditions, the ideal concrete cover should be in the region of 50 to 75 mm. Notably, while reduced concrete cover may prove to be risky (as defects such as voids and cracks may provide a quicker and low resistance path to the reinforcement), concrete cover beyond 75 mm may also have adverse effects (as it may lead to excessive surface crack widths) (Mackechnie, 2001).

c) Severity of exposure

Factors such as the distance from the ocean and climate determine the severity of marine exposure. There are two marine categories currently provided by the current codes:

1. Very severe exposure – Where RC structures are subjected to mild abrasion/wave action or spray; and
2. Extreme exposure - Where RC structures are subjected to excessive abrasion action of the ocean (Mackechnie, 2001).

d) Site practice

Inadequate placing, insufficient compaction and poor curing methods negate the benefits of having an optimal design containing the best material selection. Good site practice such as active moist curing has proven to improve the surface properties of concrete. It should be noted that a significant cause of concrete durability problems is the inability to ensure consistent quality on site (Mackechnie, 2001).

2.3 Chloride Transport in Concrete

Concrete is intrinsically a porous material. Macro-pores and micro-cracks exist on the concrete surface which provides a path for aggressive ions to be transported (Aguiar, Camões & Moreira, 2008). Many deterioration mechanisms such as corrosion, carbonation or leaching are associated with the ease with which an ion or fluid transports through the concrete's microstructure. The potentially aggressive species passageway is influenced primarily by the concrete's penetrability. Concrete penetrability is defined as its ability in which it permits the transport of liquids and gasses through it (Alexander, Bentur & Mindess, 2017). Limiting the movement of gases and fluids through concrete results in a more durable RC structure (Stanish, Hooton & Thomas, 2004).

The concrete cover provides a physical barrier that protects the reinforcement from the ingress of chlorides in marine environments. However, most RC structures that experience a mechanical load or thermal shrinkage behave in a cracked state, leading to an increased risk of corrosion. The presence of cracks allows for a rapid diffusion (which is discussed in more detail below) of chloride ions and premature initiation of reinforcement corrosion (Li, Liu & Wang, 2017). Studies by Li, Liu & Wang (2017) indicate that the chloride concentration and the crack width should be limited to control the corrosion rate for cracked RC structures.

Chloride ions from de-icing salts and ocean water are a major threat to the reinforcement in RC structures (Dyer, 2014). A typical chloride profile is shown in Figure 2-5, illustrating the relationship between the chloride concentration and the depth of the reinforcement bar. It can be seen that the chloride ion concentration reduces with depth.

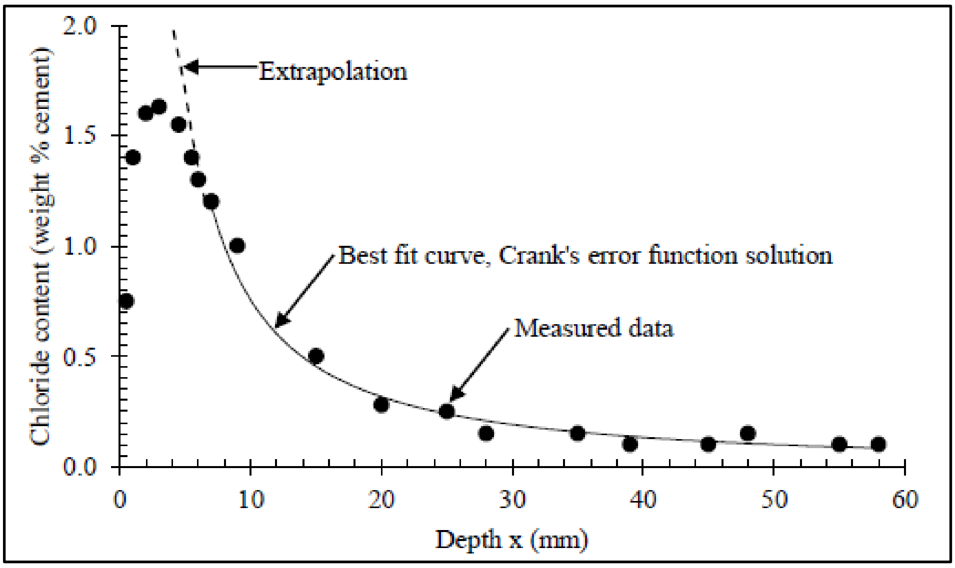


Figure 2-5: Typical Chloride Profile from a Splash Zone (Alexander, Beushausen & Otieno, 2012)

These chloride ions may enter the concrete surface from the environment through various transport processes, including a concentration gradient also known as diffusion, a pressure gradient that causes the chloride-bearing solution to flow through the pores, capillary action and migration. These mechanisms are explained below.

2.3.1 Diffusion

Diffusion occurs when liquid or gas molecules move from a high to a low concentration to achieve system equilibrium. Gaseous diffusion occurs in unsaturated concrete, while ionic diffusion occurs in saturated or partly saturated conditions. The diffusion theory is based on Adolph Eugen Fick's models (Poulsen & Mejlbro, 2006). The modelling of ionic and gaseous diffusion in a uniformly permeable material, such as concrete, is generally performed using Fick’s First Law see equation 2.3 below (Poulsen & Mejlbro, 2006). This equation is suitable when there is no change in concentration with time, i.e., steady-state conditions. For non-steady-state conditions, Fick’s Second Law may be used. See equation 2.4 below (Stanish, Hooton & Thomas, 2004).

Fick’s First Law – Steady-state diffusion

$$J = -D\frac{dC}{dx} \tag{2.3}$$

where: J = mass transport rate (g/m^2/s)

D = effective diffusion coefficient (m^2/s)

C = concentration of fluid (gas or ion)

x = distance (m)

Fick's Second Law – Non-steady state diffusion

$$\frac{\partial C}{\partial t} = -D\frac{\partial^2 C}{\partial x^2} \qquad (2.4)$$

where: t = time (s)

Diffusion is the principal transportation process for RC structures that are completely submerged in ocean water or salt-contaminated soil, and it is directly dependent on the porosity of the concrete (Stanish, Hooton & Thomas, 2004). A low rate of diffusion or low diffusion coefficient is attained when the total volume fraction of porosity is low (Dyer, 2014).

Cracks in concrete are instrumental in prompting chloride diffusion. These cracks can be avoided by facilitating proper placement, curing and correct mix compositions (Smilauer, Jendele & Cervenka, 2013). The cracks allow unobstructed paths for the chlorides to enter through the concrete cover. As the crack width is substantially more extensive than the pore widths, the cracked concrete displays significantly higher diffusion coefficients (Dyer, 2014).

2.3.2 Permeation

The flow rate of the chloride solution into concrete, under a pressure difference, depends on the concrete's permeability, which is strongly influenced by the pore structure. Cracking also accelerates the rate of flow through concrete. (Dyer, 2014).

2.3.3 Capillary action

When the water reaches the unsaturated pores at the concrete surface, it will be drawn into the concrete by capillary action. If chlorides are dissolved in the water, it will further encourage chloride ingress. The hydraulic diffusivity and the gradients of volume saturation influence the rate of water uptake by the concrete (Dyer, 2014).

2.3.4 Migration

The movement of ions in a solution under an electrical field is called migration. This is described by the Nernst-Planck equation, see equation 2.5, and is most commonly used in laboratory accelerated chloride tests. The Nernst-Planck equation is as follows (Andrade, 1993):

$$v = \left(D\,\frac{zF}{RT}\right)\left(\frac{dU}{dx}\right) \qquad (2.5)$$

where:

v = velocity of ionic species

D = diffusion of the ionic species

z = electrical charge (ionic valence)

x = Faraday's constant

T = absolute temperature

U = potential difference across the sample

Z = distance variable

R = universal gas constant 98.314 j/molK)

2.4 Conclusion

The marine environment provides a severe test of durability for reinforced concrete structures due to the nature of the chemical and physical attack. The concrete may deteriorate rapidly unless the structure is well-designed and built with quality materials.

Steel reinforcement corrosion is the most dominant mechanism of damage to concrete structures in marine environments, as it may result in significant damage to both the steel reinforcing steel (loss of cross-section) and the concrete (cracking, delamination, spalling).

Factors such as binder type, cover to reinforcement, severity of exposure and construction practice have a great influence on durability performance. The concrete cover essentially provides most of the protection for the structure.

The chloride ions may enter the concrete surface from the environment through various transport processes, including a concentration gradient also known as diffusion, a pressure gradient that causes the chloride-bearing solution to flow through the pores, capillary action and migration. The design technique proposed for predicting chloride levels in marine concrete is using a modified solution of Fick’s law of diffusion.

3. Surface Treatment Systems

3.1 Introduction and Background

Surface treatments are commonly applied to RC structures in marine environments to either improve their appearance or to protect the structure from the ingress of aggressive agents and their associated damage (Mays, 2003). Engineers and concrete practitioners have recognised an increasing need to provide additional protection to RC structures exposed to harsh environments. As a result, various protection methods are adopted, the most common and the most effective being the use of protective surface treatments on concrete (Almusallam et al., 2003). A wide variety of concrete surface treatment systems are obtainable on the market, which claim to assist in protecting RC structures by preventing reinforcement corrosion (Owens, 2009). These surface treatments range from silicones, siloxanes, and silanes to cementitious coatings (Dodge Woodson, 2009).

3.2 Surface Treated Concrete

Concrete is a naturally porous material. The distribution and size of the pores vary and are dependent on a list of factors such as; the material used in the mix design, the quality of the compaction when placing it, the degree of hydration, w/c ratio, and type and length of curing. These pores create a network that can be penetrated by gas, water, or ions (Christodoulou et al., 2013).

The durability of concrete may be improved by applying surface treatments to the concrete (Basheer & Cleland, 2011). The variety of surface treatments currently available on the market makes the selection of the most appropriate surface treatment challenging, as each treatment provides varying levels of protection, even those with similar chemical compositions. Factors such as; the coating's durability, the environment and the original substrate condition may affect the protection provided by the coating (Khanzadeh Moradllo, Shekarchi & Hoseini, 2012).

Surface protection treatments are the primary protection method used to protect new and existing RC structures in the marine environment by limiting chloride penetration (Khanzadeh Moradllo, Shekarchi & Hoseini, 2012). Basheer & Cleland (2011) state that siloxanes and silanes have been extensively used on RC structures in the USA and the UK. These treatments penetrate the concrete and react with the hydration pores to form a hydrophobic pore lining. The pore-lining reduces the level of moisture and chloride ions by as much as 98 % of that of untreated concrete. Treated concrete surfaces show a reduction in chloride ingress, causing a noticeable delay in corrosion initiation. A thorough review of various surface treatment systems is set out herein below.

3.3 Types of Surface Treatment Systems

One of the most popular means of preventing harmful substances from penetrating the concrete surface is to apply a surface treatment system (protective layer) on the concrete surface (Mays, 2003).

Surface treatment systems can be classified into two categories namely organic and inorganic treatments. Organic surface treatment systems are extremely popular as they provide effective surface protection. However, their limited-service life, poor fire resistance, and ease of cracking and detachment raise concerns among practitioners. They are also tough to remove after their protective effects are lost (Pan et al., 2017). Although less research has been conducted on inorganic surface coatings, they are known to have a far superior durability performance and superior resistance to ageing (Pan et al., 2017).

Grantham (2011) highlights certain factors that should be considered when applying surface treatments, which relate to the age and the condition of the RC structure as set out in Table 3-1 below:

Table 3-1: Factors to be considered when applying surface treatments (Grantham, 2011)

Age and Condition	Description
New RC structures in satisfactory condition: ‘normal specification’ of surface treatment	Surface treatment systems would generally be specified during the design stage, where there is a concern about the concrete’s performance in an aggressive environment, predominantly for the prevention of direct deterioration or to control ingress. These are steps taken over and above the commonly used practices, such as increasing concrete cover and improving the concrete mix.
New RC structures in unsatisfactory condition: ‘remedial specification’ of surface treatment	Surface treatment systems may also be applied to RC structures to alleviate potential deterioration due to inadequate designs and/or bad workmanship, such as insufficient concrete cover and inadequate mix designs.
Deteriorated RC structures: ‘repair specification’ of surface treatment	Where deterioration due to physical and chemical effects has already occurred, applying a simple surface treatment at an early stage may be feasible. For RC structures that have been in service for an extended period, an assessment should be carried out to identify if reinforcement corrosion has already been initiated, and a decision on the suitability of a specific treatment should be made.

This dissertation critically examines the protective benefits and shortcomings of surface treatments applied to RC structures in marine environments. A particular focus will be on the service life extension and the durability enhancement that these treatments have on RC structures in the marine environment.

Surface treatments are categorized by how they offer protection and not necessarily by their material composition (Mays, 2003). The primary reason for applying surface treatments is to reduce the occurrence of reinforcement corrosion and its associated damage (Mays, 2003). Mays (2003) and Dyer (2014) explain that surface treatments are classified into four types of surface protection systems namely; surface coatings, hydrophobic impregnations, impregnations or surface sealers and screeds and overlays, which are discussed in detail in the subsequent chapters and are clearly distinguished diagrammatically in Figure 3-1 below.

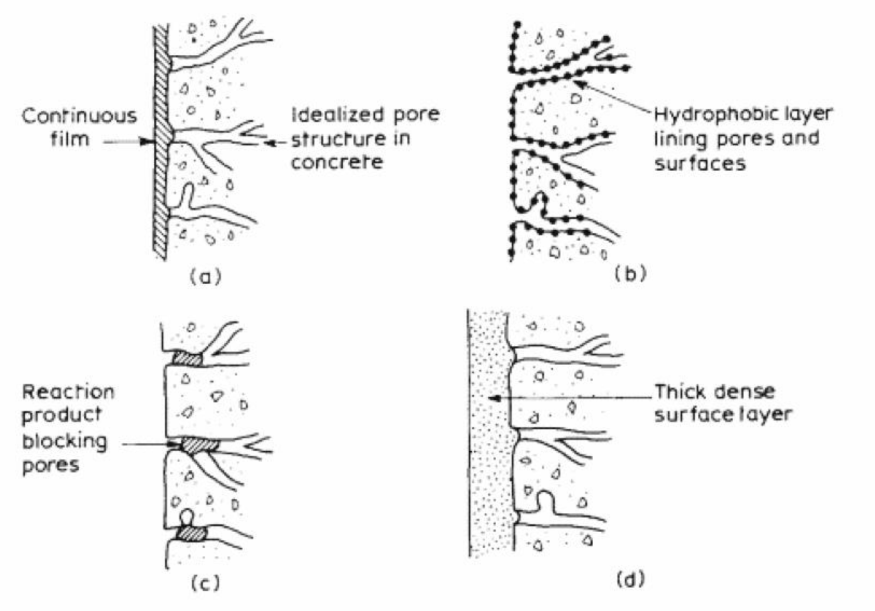


Figure 3-1: Surface treatment classes (a) Surface Coatings (b) hydrophobic impregnations (c) Impregnations or surface sealers (d) Screeds and overlays (Mays 2003)

3.4 Surface Coatings

Surface coatings create a continuous film over the surface of the concrete that acts as a barrier to prevent the passage of moisture or corrosive substances from penetrating the cementitious substrate (Pan et al., 2017). They include both organic and inorganic treatments in line with their chemical composition.

Organic coatings include those that are polymer-based, including elastomers and polymers that are transferred in a solution form in either organic solvents or in water and deposited once the solvent evaporates. They also include resin systems such as alkyds, bitumen and oleoresins (resin/oil mixtures acquired from plants) that harden when applied to the concrete surface, (Dyer, 2014). Inorganic coatings comprise alkali silicate products and cementitious formulations (Dyer, 2014).

3.4.1 Function and mechanism

While sealers penetrate the concrete pores, surface coatings provide a dry film layer on the concrete surface. These coatings are applied to RC structures to ameliorate their appearance and/or to protect the RC structure from having aggressive agents entering it. The surface coating shall either extend the service life of an existing structure or enhance the durability of new structures (Mays, 2003).

3.4.2 Types

Surface coating systems include organic and inorganic formulations based on different material compositions. Organic systems comprise the following:

- Polymers and elastomers - Are delivered in the form of solutions in either organic solvents or water and deposited as the solvent evaporates (See a) below);
- Resin systems – Which harden when applied to the concrete surface;
- Alkyds (fatty acid-modified polyesters);
- Bitumen; and
- Oleoresins (oil/resin mixtures acquired from plants) (Dyer, 2014).

Inorganic systems comprise the following:

- Cementitious formulations (See b) below), and
- Alkali silicate products (Dyer, 2014).

a) Coating systems based on polymers

These coating systems provide a continuous dense protective layer on the concrete surface, typically between 0.1 and 5 mm thick. They are applied to prevent the ingress of harmful substances, bridge cracks and increase the concrete's mechanical resistance. Coatings may be applied in many layers to meet the requirements set out in BS EN 1504 (Raupach & Büttner, 2014). These requirements are set out in detail in chapter 4 of this report.

The four failure patterns observed on polymer-based coatings are cracking, holes, blistering and peeling. Cracking is likely caused by the shrinkage of the coating due to temperature changes or the cracking of the substrate. Osmotic pressure or uneven painting could cause pores and holes, which increases the permeability of the coating. The partial loss of adhesion indicates blistering, which may also result from osmotic pressure. Peeling is attributed to the loss of adhesion, typically caused by the penetration of aggressive substances in the concrete substrate (Pan et al., 2017).

A levelling layer may be required to ensure that the layers are applied in a consistent thickness, which will mitigate the premature failure of polymer-based coatings. This layer usually comprises a polymer-modified cement mortar with a maximum aggregate size of 0.5 mm and a maximum thickness of 3 mm. The protective layer that follows should have one or more of the following qualities:

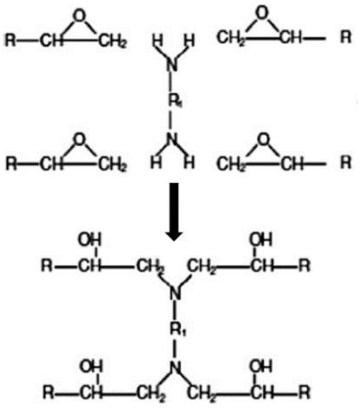
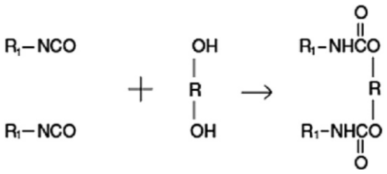
- Impermeable to CO_2;
- Impervious to water and harmful substances;
- Crack bridging;
- Resistance to chemical attack;
- Resistance to mechanical impact (Raupach & Büttner, 2014).

The construction industry traditionally uses epoxy resins, acrylic and polyurethane coatings. Polyurethane coatings protect RC structures with no shrinkage and have a high resistance to acid attack. While acrylic coatings have good alkali resistance, oxidation, and weathering, their ductility and bonding strength is inferior to that of epoxy resin coatings (Pan et al., 2017). Table 3-2 provides a summary of the advantages and disadvantages of polymer-based coatings.

Polyurethanes are thermos-set polymers that are produced by the reaction of polyol and polyisocyanate. They contain one pendant hydrogen molecule that takes part in hydrogen bonds. This bond allows for high tensile strength in high-stress conditions and high hardness in low-stress conditions. Furthermore, the high cross-link density of such coatings produces high chemical resistance and tensile strength needed to reduce chloride ion ingress (Sadati, Arezoumandi & Shekarchi, 2015).

Acrylic coatings, typically methacrylic or acrylic acids, are long-lasting, UV resilient, and high weather-resistant, and considerably reduce chloride and water penetration into concrete (Sadati, Arezoumandi & Shekarchi, 2015).

Table 3-2: Properties, advantages and disadvantages of polymer-based coatings used for surface treatment (Pan et al., 2017)

Type	Curing Mechanism	Advantages	Disadvantages
Epoxy resins		Easy to cure; Low shrinkage; Good adhesive strength and chemical resistance	Low impact strength; Low fracture energy; Low thermal stability; Poor hydrophobicity; Prone to weathering; Poor resistance to the initiation and propagation of cracks
Acrylic	Physically drying	High resistance to UV and hydrolysis; Good alkali resistance	Low bond strength; Poor ductility; Generally, not applied for constant immersion in soil or water
Polyurethane		Excellent resistance to weathering: self-healing; no shrinkage	Poor resistance towards mechanical strains and degradation and/or deformation at high temperatures

b) Coating systems based on cementitious materials

Polymer-modified cementitious coatings are the most used cementitious coating used to protect RC structures. Cementitious coatings form a low permeability layer, with an estimated thickness of between 2 and 3 mm. They are modified using polymers, mainly polyurethane, acrylic, or epoxy, and fine aggregate and cement. Adding a polymer significantly improves the coating properties of strength, adhesion, resilience, impermeability, and chemical resistance. Polymer-modified cementitious coatings provide additional protection to RC structures by:

1. Forming a net structure in the hardened cement paste which reduces surface micro-cracking.

2. The pore structure of polymer cementitious coatings differs from ordinary Portland cement. Pores smaller than 100 nm increase, while pores larger than 100 nm decrease in polymer-modified mortar.
3. Mitigating shrinkage.
4. Due to their relatively low elastic modulus, they have good “crack-bridging” and “breathability” attributes.
5. They have very high UV resistance and can bridge existing cracks and maintain their protective effect for an extended period (Pan et al., 2017).

3.4.3 Factors influencing performance

The selected surface coating system should protect the RC structure from the specific damage it is experiencing or might experience in the future (Safiuddin, 2017). The surface coating’s effectiveness is primarily based on the condition to which the RC structure is exposed during the application process and in service. Moreover, the state of the concrete substrate and the methods used in preparing the substrate also play a pivotal role in the performance of the selected surface treatment. The factors shown in Table 3-3 below will influence the coating’s selection and performance (Safiuddin, 2017).

Table 3-3: Factors to be considered during the selection of surface coatings (Safiuddin, 2017)

Specific Factor	Consideration
Type of substrate and its surface condition	New or old concrete, roughness, any prior treatment or contamination of the concrete surface.
Exposure condition	Marine, atmospheric, or buried environment, pollutants, presence of moisture, and aggressive chemicals
Concrete Protection type	Chemical or acid attack, abrasion, alkali-carbonate reaction, alkali-silica reaction, chloride attack, carbonation, wetting and drying, freezing and thawing, sulphate attack, salt scaling, and water ingress.
Expected durability of coatings and sealers	Adhesion strength, abrasion resistance, chemical resistance, elasticity, colour retention, film hardness, impact resistance, toxicity, moisture vapour transmission, water resistance and UV resistance.
Service condition	Load/non-load bearing condition, skid resistance, air and hydrostatic pressure
Installation of coatings	Surface preparation, installation methods, the influence of temperature, site location, and the effect of substrate moisture.
Cost of Surface Treatments	Required number of coats or coverage rate, labour costs, film thickness, maintenance and material costs.

The performance of the surface coating is dependent on how it is applied. BS 6150 sets out guidelines for selecting and applying coatings on concrete surfaces (Dyer, 2014).

Even though the manufacturers of coatings are required to provide a series of standard tests (which are further discussed below), there are several requirements that the specifier should also note. These are described below:

- There are two classes of coatings for enduring abrasion by traffic and three classes of permeability to water vapour. Thermal compatibility is split into un-trafficked or trafficked environments for adhesion after several exposure cycles, with added subdivisions such as crack-bridging and flexible or rigid systems (Grantham, 2011).

- For crack-bridging systems, the crack accommodation should be chosen by the designer, taking into account the local conditions with zero failures accepted. The impact resistance is split into three categories. Furthermore, antistatic coatings are divided into two classes, which are environment-dependent (Grantham, 2011).

a) Age and quality of concrete

Concrete with a higher cement content and a lower w/c ratio naturally performs best to guard against chloride ingress. Studies have also shown that surface coatings decreased the diffusion coefficient of chlorides on all concrete qualities (Aguiar, Camões & Moreira, 2008). Ideally, surface coatings should be applied at least one year after concrete placement (Meier & Wittmann, 2011).

b) Moisture content in the surface zone

Although research by Dyer (2014) has shown that surface coatings perform better on dry concrete, Levitt et al. (1997) explain that for optimal adhesion, the supplier’s recommendation regarding the acceptable surface moisture level should be strictly adhered to, as these levels can vary within a given generic group and are dependent on the specific formulation.

c) Surface preparation

A concrete surface typically presents several problems for coatings. Concrete surfaces are generally rough and contain blow holes, especially after high-pressure water jetting or grit blasting. It is usually dusty, friable, has a weak laitance layer, and holds varying degrees of absorbance (Levitt et al., 1997).

Due to these surface irregularities, a form of levelling may be essential. This is done to ensure that the supplier’s recommended film thickness is achieved and a satisfactory continuous barrier is provided (Levitt et al., 1997) and (Raupach & Büttner, 2014). A low-viscosity primer/sealer is applied to the surface to make the surface absorbency more uniform. This product inherently stabilizes dusty and friable surfaces before the top coat is applied (Levitt et al., 1997).

It is well documented by Levitt et al. (1997) that performance is not necessarily increased by applying a thicker than recommended coating. Excessively thick coatings may result in solvent entrapment and consequent failure, i.e., loss of adhesion and blistering. When a greater film thickness is preferred, the number of coats applied should be increased rather than increasing the coating thickness.

Dyer (2014) suggests that all efflorescence be ceased before applying a surface coating. He also highlights the sensitivity of some organic coatings to the alkaline conditions present on the concrete surface. In some instances, alkali-resisting primers are used to enhance the performance.

3.4.4 Performance in marine environments

Due to the high concentration of chloride ions in marine environments, chloride ions, along with water molecules, tend to penetrate the concrete surface, causing reinforcement corrosion. Various factors influence the performance of surface coatings in the marine environment, which are discussed below. They include the varying degrees of protection based on varying compositions, the effect on the transportation of chloride ions and water molecules through the concrete, the effect that the cover depth has on the performance and how it may extend the service life of RC structures.

a) Varying degrees of protection

Even though surface coatings could have similar generic makeups, their characteristics may differ considerably, providing varying degrees of protection. Mehta (1999) explains that surface coatings, when applied to a concrete surface, have a lengthy but chequered history of effectiveness regarding the protection from chloride attack. This is mainly since surface coatings with similar generic types may vary substantially in diffusion characteristics.

b) Chloride and water transportation

Applying a surface coating such as a polyurethane coating, an epoxy-based polymer coating, or a cementitious coating to an RC structure's surface is a feasible and cost-effective solution for protecting RC structures in marine environments. These coatings, as discussed below, have proven to provide protection against the ingress of chlorides and moisture.

Results from the research by Medeiros & Helene (2009) indicated that polyurethane coatings successfully inhibited water penetration. This coating is commonly used on RC structures in marine environments, as water can be a vehicle for chloride penetration. Further evidence of the efficacy of the polyurethane system is seen in the sorptivity tests conducted by Medeiros & Helene (2009), in which the coating reduced the sorptivity by 90 %, compared to hydrophobic agents, which showed a reduction in sorptivity by about 70 %. In addition, an impressive 86 % reduction in chloride diffusion coefficient was observed, making it significantly more chloride resistant than hydrophobic agents.

Epoxy-based polymer surface coatings fill the pores of the concrete, concealing the external surface and thus making it less permeable. Testing by Aguiar, Camões & Moreira (2008) and Dacuan et al. (2021) confirmed that epoxy-based polymer surface coatings provided increased protection against the penetration of chlorides by significantly reducing the diffusion coefficient.

Cementitious coatings may assist with both the initiation and propagation stages. During the initiation phase, it essentially creates a barrier against chloride penetration. Indirectly, the coating also regulates the exchange of water vapour between the external environment and the concrete, thereby influencing the concrete’s water content. Consequently, applying cementitious coatings to an RC structure that is exposed to the marine environment could reduce the water content, and since ion migration only occurs in an aqueous phase, it also reduces the rate of chloride diffusion in concrete (Diamanti et al., 2013). Tests by Diamanti et al. (2013) showed that the protective effect produced by cementitious coatings, modified with acrylic polymers, slowed down the rate of chloride penetration and lessened the water content of concrete in wet environments. These coatings also produced an effective physical barrier under wet-to-dry cyclic exposure conditions, delaying water absorption. Furthermore, the authors noted that the protective effect was more pronounced when the polymer-to-cement ratio was increased from 0.35 to 0.55. This was attributed to the twofold effect of increasing the surface hydrophobicity and reducing the coating porosity.

c) Concrete cover depth

The existing concrete cover depth vastly influences the efficacy of surface coatings in marine environments. de Medeiros et al., (2016) explain that the larger the concrete cover, the greater the surface protection gain is in years, thereby extending the service life of RC structures in marine environments. It would be useful to further investigate these claims, as it is almost intuitive to think that the efficacy of the surface treatment relies solely on itself.

According to the studies by (Medeiros & Helene, 2009; Medeiros et al., 2012), the surface coating protection can be converted to an equivalent concrete cover depth. Results showed that a polyurethane coating provided an equivalent additional cover depth of 34 mm. As increasing the concrete cover may not always be practical or in some instances aesthetically pleasing, the equivalent additional cover depth provided by the surface treatment system may fundamentally change the way RC structures in marine environments are designed and maintained in the future.

d) Service life extension

Surface coatings increase the service life of RC structures in marine environments. Dacuan et al. (2021) found that RC structures coated with a polyurethane coating exhibited lower corrosion rates and shallower cracks compared to control specimens. The tests conducted by Medeiros & Helene (2009) indicate that applying a polyurethane coating to an RC structure could increase its service life by as much as 7.8 times when compared to uncoated RC structures.

3.4.5 Principle performance overview

This section provides an overview of the characteristics that surface coatings offer. Table 3-4 is reproduced using the guidelines described in (Shaw, 2009). Table 3-4 explains how the different principle performance characteristic classes provide protection at different levels.

Table 3-4: Overview of the characteristics of surface coatings (Shaw, 2009)

Principle Performance Characteristics	**Ingress Protection**	**Moisture Control**	**Physical Resistance**	**Chemical Resistance**	**Increase Resistivity**	**Key Requirements**
Permeability to CO_2	√	-	-	-	-	- Continuous protective layer. - Thickness of 0.1 mm - 5.0 mm - Typically, organic polymers
Permeability to Water Vapour Class 1: SD < 5m (Permeable to water vapour) Class 2: 5m $\leq$SD$\leq$50m Class 3: SD>50m)not permeable to water vapour)	√	√	-	-	√	
Capillary absorption and permeability to water $W<0.1kg/m^2.h^{0.5}$	√	√	√	-	√	
Resistance to severe chemical attack Class 1: 3 days without pressure Class 2: 28 days without pressure Class 3: $\geq$ 28 days with pressure	-	-	-	√	-	
Impact Resistance After impact, no cracks or delamination Class 1: >4Nm Class 2: $\geq$10Nm Class 3: $\geq$20Nm	-	-	√	-	-	
Adhesion strength (Pull-off Test) Average (N/mm^2) **Rigid Systems** Without trafficking $\geq$1 With trafficking $\geq$2 **Crack bridging/flexible systems** Without trafficking $\geq$0.8 With trafficking $\geq$1.5	√	√	√	√	√	
Abrasion Resistance Taber test $\leq$3000mg abrading	-	-	√	-	-	
SD – Water vapour diffusion resistance factor W – Rate at which water is absorbed						

3.5 Hydrophobic Impregnations

These liquid impregnants render the concrete surface hydrophobic by lining the concrete's pores and repelling moisture. The effect on the concrete surface is minimal, as no physical barrier is created on the concrete surface, thus still allowing it to 'breathe'. Silane compounds, commonly alkyl trialkoxysilane compound monomers, such as silane and isobutyl, are the most widely used hydrophobic agents on concrete surfaces. The hydrophobic impregnation causes the water droplets in contact with the surface of the concrete to form a large contact angle, see Figure 3-2 below. The benefit of having a large angle is that the surface water allows for minimal contact with the concrete, thereby limiting the extent to which the water can enter the concrete pores. This also essentially eliminates capillary action, as the concrete pores are lined with silanes (Dyer, 2014).

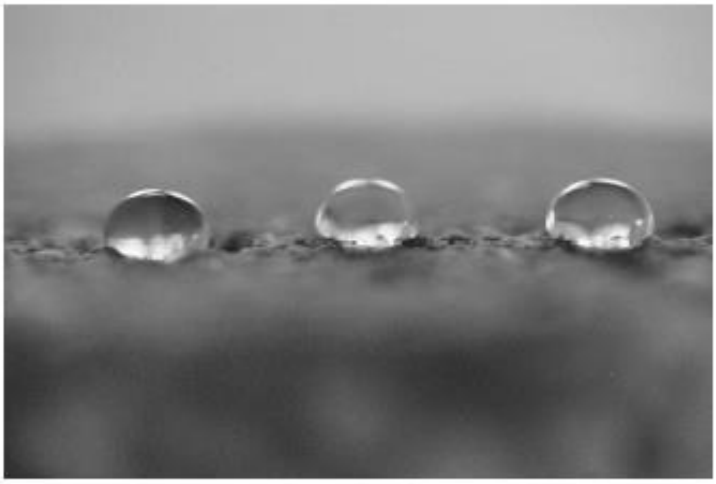


Figure 3-2: Water droplets on a concrete surface treated with a hydrophobic agent
(Raupach & Büttner, 2014)

These protective coatings react with the cement-based materials when coated thereon and drive the hydrophobic alkyl to create a lamellar protective coating layer on the surface, resulting in the capillary pore walls being lined. This effectively inhibits the water molecules and ions from entering the concrete's capillary channels (Li et al., 2019).

BS EN 1504-2 classifies hydrophobic impregnants appropriate for use when moisture control, ingress protection and increasing resistivity are necessary. Hydrophobic impregnants are identified as class 1 if their penetration depth is <10 mm and class 2 if greater penetration depths are achieved (Dyer, 2014).

3.5.1 Function and mechanism

The key advantage of using hydrophobic treatments on the surface of RC structures in marine environments is its ability to create a water-repellent surface without affecting the water vapour transport through the material, as well as not changing the surface appearance. The hydrophobic treatment covers the pore walls without filling the pores, creating an increased contact angle of the pore wall, as shown in Figure 3-2 above.

Through capillary action, water is rapidly transported in non-saturated pores. The absorption rate is a function of the density and viscosity of the liquid, the surface tension and the contact angle between the pore walls and the liquid. In untreated concrete, the contact angle is <90º due to the molecular attraction between the water and the cement paste (hydrophilic behaviour). The water droplets are spread flat on the concrete surface resulting in the suction of water by means of capillary rise (Tepfers, 2009).

By covering the capillary walls with silane molecules, the walls become devoid of ionic electrical charges and the water is no longer attracted to the surface of the concrete. Internal hydrogen bonds hold the water molecules together by creating layers or droplets with angles >90º outside the capillaries (Tepfers, 2009). Hydrophilic and hydrophobic capillaries are depicted in Figure 3-3, while the interaction between water and a hydrophobic material is shown in Figure 3-4.

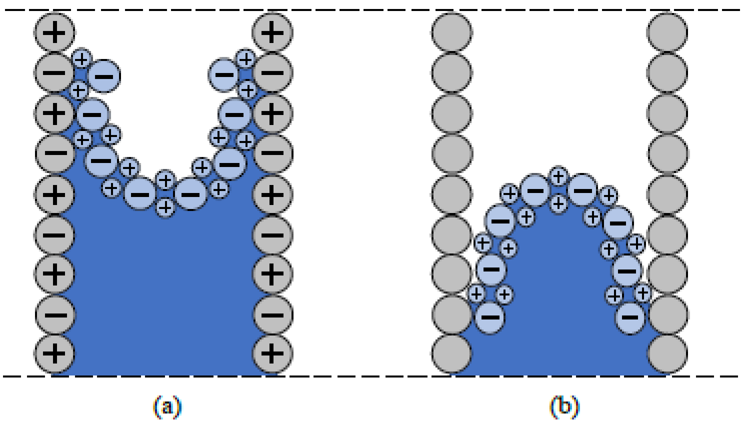


Figure 3-3: Water Intrusion a) Hydrophilic capillary b) Hydrophobic capillary (Tepfers, 2009)**.**

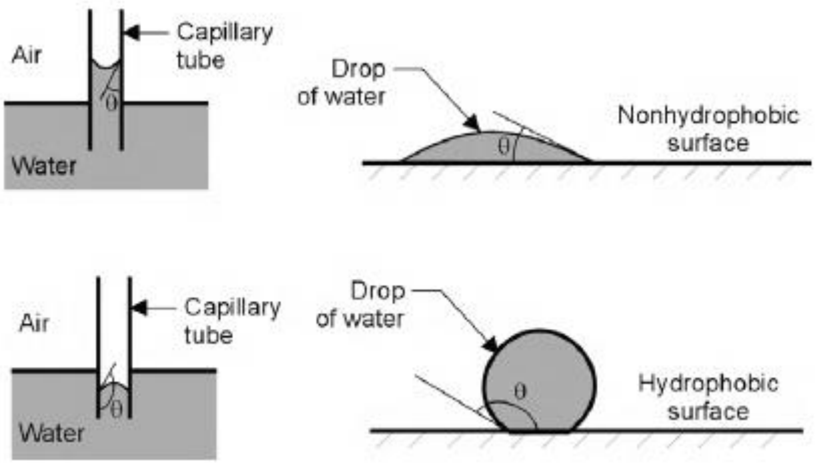


Figure 3-4: Interaction between water and a hydrophobic material and a non-hydrophobic material (Bertolini et al., 2013)

3.5.2 Types

Hydrophobic impregnations have varying material compositions, influencing the application technique and affecting the level of protection provided. Hydrophobic impregnations are generally applied as a film to a concrete surface to significantly reduce water uptake and dissolved aggressive agents, such as chloride ions. These products are typically dissolved in a solvent, either alcohol or water, and depending on its viscosity, applied to the concrete surface by brushing or spraying, as depicted in Figure 3-5. The products currently on the market are either creamy or water-like. While all the materials evaporate after the application, the creamy products tend to evaporate at a slower rate, thus resulting in a deeper penetration, which has been shown to be more effective and offers higher protection (Raupach & Büttner, 2014).

Figure 3-5: (left) Silane-based cream (right) liquid (Sika, 2016)

Silanes from the silicone group are most commonly used for hydrophobizing concrete. Silanes are small molecules (1.0-1.5 x 10^{-6} mm diameter) with one silicon atom, while siloxanes (1.5-7.5 x 10^{-6} mm diameter) comprise a few silicon atoms in short chains, as presented in Figure 3-5. These small molecules permit them to penetrate highly dense substrates (Pan et al., 2017). Silanes and siloxanes contain organic alkoxy groups linked to silicon atoms, which react with the silicates from the concrete pore-wall surface to create a stable bond resulting in water molecules being repelled (Bertolini et al., 2013).

The chemical reaction between the concrete substrate and the silane is shown in Figure 3-6. The silane hydrolysis reacts with water in the capillary pores. The unstable silanol molecules then lose the water and condensate into silicon resin. Consequently, the silicon resin and silanol groups react with the hydroxyl ground in the substrate through hydrogen bonds. Lastly, during drying, the silicon resin bonds to the substrate providing a water-repellent effect. The concrete's alkalinity performs as the catalyst in this reaction (Pan et al., 2017).

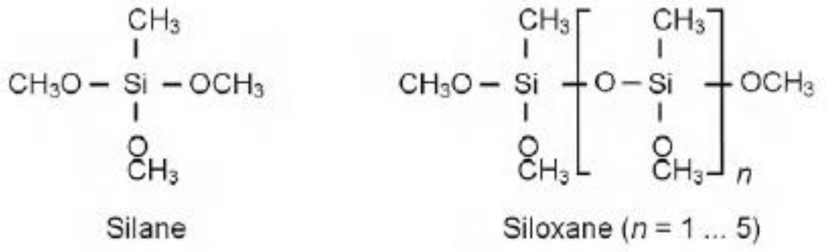


Figure 3-5: Silane and siloxane molecules (Bertolini et al., 2013)

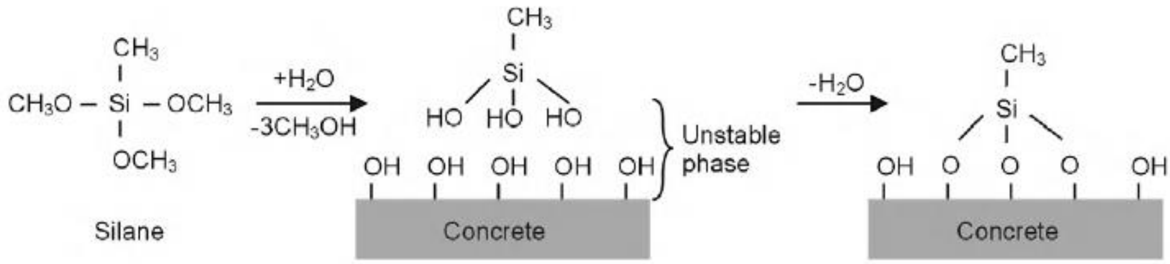


Figure 3-6: Reaction of silane with a concrete substrate (Bertolini et al., 2013)

Even though the manufacturers of hydrophobic impregnations are required to provide a series of standard tests (which are further discussed below), BS EN 1504 states that the specifier should also note several requirements. This includes the fact that there are two classes relating to the depth in which the material penetrates the concrete: class 1: <10 mm and class 2: >10 mm. Similarly, there is a performance characteristic for the diffusion of chloride ion resistance, as well as two classes for the drying rate coefficients (Grantham, 2011).

3.5.3 Factors influencing performance

The performance of hydrophobic impregnations on concrete surfaces is characterised by their ability to reduce capillary water absorption and chloride ion concentration. The service life and performance of the treatment mainly depend on three parameters: The type of treatment used, its penetration depth and the amount of water-repellent agent used (Meier & Wittmann, 2011).

The penetration depths primarily depend on the contact time between the water-repellent agent and the concrete surface and the w/c ratio of the concrete. Penetration depths can be increased by repeating the brushing or spraying of the liquid treatment. Research has shown that if a liquid silane is applied to a surface and maintained for 120 minutes, a penetration depth of 17 mm is reached. However, if the same treatment is applied and maintained for 5 minutes, a penetration depth of only 4.5 mm is achieved (Meier & Wittmann, 2011). Figure 3-7 below shows penetration depths using different treatment types on concrete with a w/c ratio of 0.5.

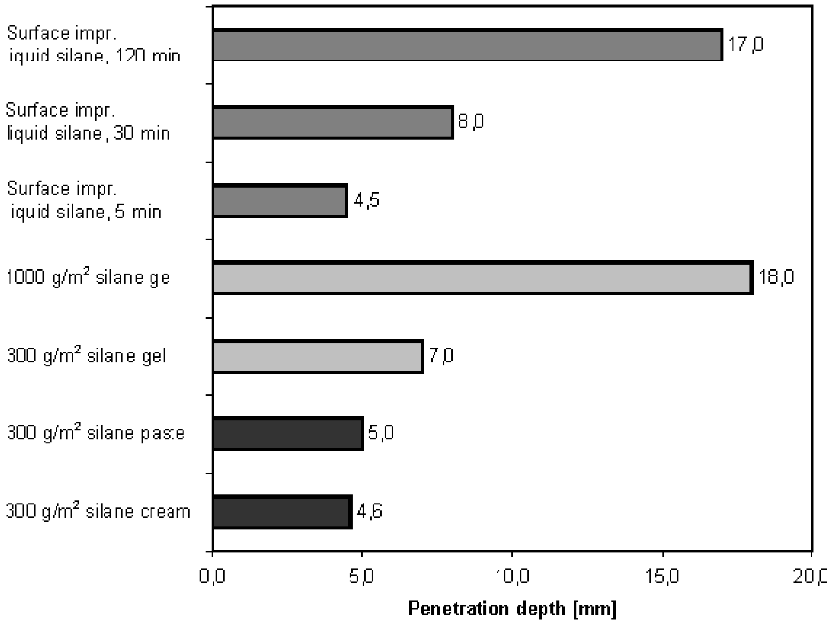


Figure 3-7: Penetration depths using different surface treatment types (Meier & Wittmann, 2011)

The penetration depth is further governed by the type of hydrophobic agent applied as well as several parameters such as:

a) Age and quality of concrete

According to Meier & Wittmann (2011), one year should lapse before treatment is applied to the concrete, as this would allow sufficient time for the moisture content to be lowered. If this is not possible, then the age of the concrete should be at least one month. Studies have shown that it is good practice to apply hydrophobic impregnations in two stages. The first treatment prevents new water absorption and allows the drying process to continue, while the second treatment provides sufficient penetration depth, as the moisture content in the near-surface zone is low enough.

Furthermore, hydrophobic surface treatments were shown to perform well in concrete with a high w/c ratio, as shown in Figure 3-8, as the concrete is generally more porous than concrete with a low w/c ratio.

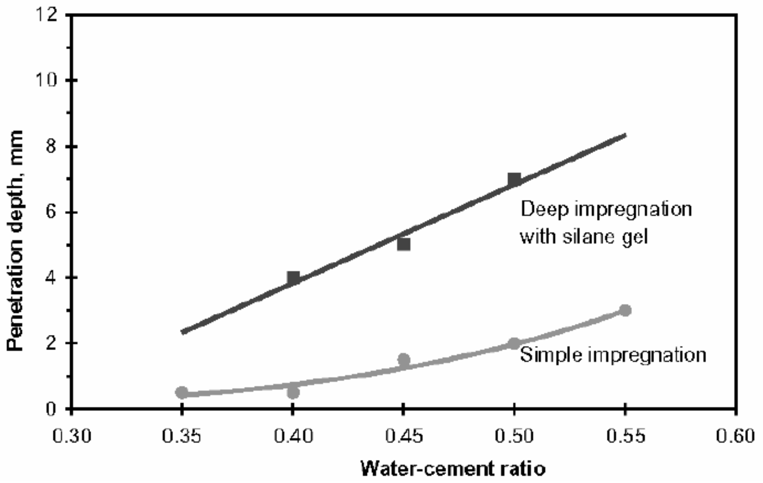


Figure 3-8: Influence of quality of concrete on penetration depth (Meier & Wittmann, 2011)

The efficiency of a hydrophobic impregnation coating on existing RC structures in marine environments that already show signs of cracking relies essentially on the hydrophobic agent's penetration depth (Dai et al., 2010). Studies conducted by Dai et al. (2010) prove that after one year of accelerated wet/dry cycles, no signs of reinforcement corrosion were evident, even though cracks as wide as 0.2 mm were measured before applying a silane agent. However, if larger cracks form after the hydrophobic impregnation is applied, chloride ingress cannot be prevented unless further treatment is carried out.

b) Moisture content in the surface zone

The near-surface zone should have a low moisture content. The study by Meier & Wittmann (2011) proves that hydrophobic impregnation treatments cannot treat concrete with a high relative humidity between 93 % and 100 %. Their tests also indicate that the lower the water content, the deeper the treatment will penetrate, as the concrete is more porous. See Figure 3-9 below.

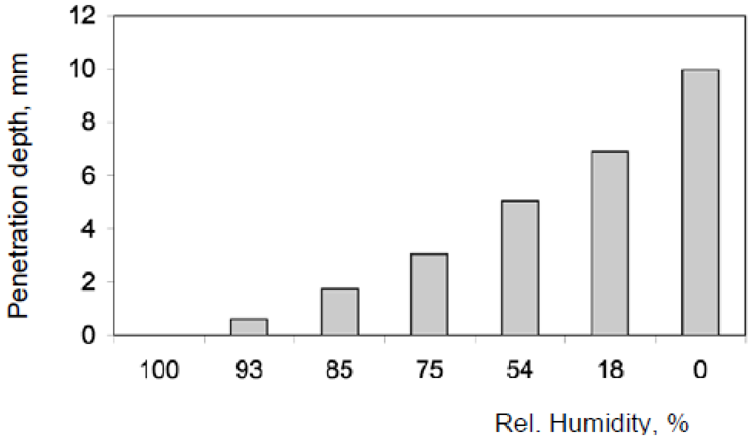


Figure 3-9: Penetration depth of a hydrophobic agent into concrete with a varying relative humidity of the surrounding air (Meier & Wittmann, 2011)

c) Surface preparation

Removing dust and dirt layers on old concrete before applying any hydrophobic impregnation treatment is essential. In marine environments, surfaces are not uncommon to be covered by microorganisms, which need to be removed before applying surface treatments (Meier & Wittmann, 2011).

3.5.4 Performance in marine environments

Due to the high concentration of chloride ions in marine environments, chloride ions, along with water molecules, tend to penetrate the concrete surface, causing reinforcement corrosion (Li et al., 2019). Various factors, as discussed below, influence the performance of hydrophobic impregnation in the marine environment. These include the duration of the protection, the aspects that affect the deterioration of the treatment, the effect on the transportation of chloride ions and water molecules through the concrete, the constituents that affect the depth that the product can reach, the impact that the cover depth has on the performance and how it may extend the service life of RC structures.

a) Durability of protection

Hydrophobic impregnations that contain silanes have long-lasting protective benefits and successfully prevent the penetration of chloride ions and water molecules into RC structures. Studies by Li et al. (2019) reveal that in the initial stages of marine exposure, a silane emulsion, a silane compound emulsion, and a silane compound gel resisted chloride ions effectively. However, as the marine exposure time increased, the protective effect of all three coatings declined. Khanzadeh Moradllo, Sudbrink & Ley (2016) showed that after 12 years of service, 100 % of the bridge decks tested had a silane layer greater than the minimum specified. A steady decline followed, resulting in a reduction of silane layer thickness by 75 % in years 17-20. Christodoulou et al. (2013) confirm that hydrophobic surface treatments that are as old as 20 years may still be present and may continue to offer a residual protective effect. As such, it is evident that surface treatments containing silanes are highly effective in treating RC structures for water and chloride ingress during the early phases following the application thereof, with a gradual decline over time. It must be noted that these treatments should, however, be reapplied before it has wholly deteriorated to avoid losing their positive effect.

b) Deterioration of the treatment

The deterioration of silane treatments can be argued to be related to the concrete’s alkaline pore solution. Khanzadeh Moradllo, Sudbrink & Ley (2016) confirm that whilst abrasion, UV light and external moisture are not significant deterioration mechanisms of hydrophobic surface treatments, it appears that deterioration caused by the alkaline pore solution is substantial. However, to lower the alkalinity of the pore solution and potentially delay its attack on the treatment, the calcium hydroxide levels are required to be reduced. This can be achieved by using high doses of concrete admixtures such as silica fume, fly ash and slag, which are known to reduce the levels of calcium hydroxide.

c) Chloride and water transportation

Silane-containing hydrophobic impregnations have the ability to resist chloride ion deterioration. The contact angle determination tests found that the use of these coatings can increase the contact angle of the water molecules on the concrete surface. In the tests described in the preceding paragraphs by Li et al. (2019), the concrete surfaces were coated, and test specimens were placed in marine exposure sites in Qingdao for one year. Results showed that all three protective coatings provided good chloride ion deterioration resistance, with test specimens coated with the silane compound gel showing a decrease in the chloride diffusion coefficient of about 50 %. All three coating types increased the contact angle, transforming the hydrophilic surface into a hydrophobic surface, thus inhibiting the transportation of water molecules into the concrete.

Hydrophobic impregnation systems are commonly used to reduce chloride transport in concrete. Research conducted by Medeiros & Helene (2009) confirms that hydrophobic agents are highly efficient in inhibiting water absorption by capillary action, albeit to a lesser degree than polyurethane coatings. Moreover, results showed a reduced chloride diffusion coefficient by 9 % for the silane/siloxane dispersed in water and 17 % for the silane/siloxane dispersed in a solvent.

d) Treatment absorption depth

When the constituents of a hydrophobic impregnation treatment system form a product with a small molecular size, it tends to absorb deeper into the RC structure, thereby providing enhanced protection. Sivasankar, Stango & Vedalakshmi (2013) explain that hydrophobic impregnations that comprise Isobutyltriethoxysilane have a smaller molecular size than hydrophobic impregnations comprising silicone ester; they can penetrate deeper into the concrete, i.e., up to 12 mm. In contrast, silicone-based hydrophobic impregnations generally penetrate between 4-6 mm deep. This is why Isobutyltriethoxysilane hydrophobic impregnations provide greater corrosion resistance than hydrophobic impregnations containing silicone esters.

e) Concrete cover depth

The existing concrete cover depth vastly influences the efficacy of a hydrophobic impregnation treatment in marine environments. de Medeiros et al. (2016) conducted chloride migration tests and calculated chloride diffusion coefficients on samples treated with a hydrophobic impregnation. They explain that the larger the concrete cover, the greater the surface protection gain is in years, thereby extending the service life of RC structures in marine environments. As stated above, it would be useful to further investigate these claims, as it is almost intuitive to think that the efficacy of the surface treatment relies solely on itself.

According to the studies by Medeiros & Helene, (2009); Medeiros et al., (2012), the hydrophobic impregnation protection can be converted to an equivalent concrete cover depth. Results showed that a hydrophobic agent provided a comparable additional cover depth of 30 mm. As increasing the concrete cover may not always be practical or in some instances aesthetically pleasing, the equivalent additional cover depth provided by the hydrophobic impregnation may fundamentally change the way RC structures in marine environments are designed and maintained in the future.

f) Service life extension

Hydrophobic impregnations increase the service life of RC structures in marine environments. The reduced chloride diffusion coefficient significantly extends the service life of RC structures in marine environments. In the tests done by Medeiros & Helene (2009), applying a hydrophobic impregnation to an RC structure could increase its service life by an estimated 1.5 times compared to uncoated RC structures. Sivasankar, Stango & Vedalakshmi (2013), on the other hand, found that hydrophobic impregnations may enhance the service life by up to 4 times that of untreated RC structures during both the initiation and propagation phases in the reinforcement corrosion process.

3.5.5 Principle performance overview

This section provides an overview of the characteristics that hydrophobic impregnations provide. Table 3-5 is reproduced using the guidelines described in (Shaw, 2009).

Table 3-5: Overview of the characteristics of hydrophobic impregnations (Shaw, 2009)

Principle Performance Characteristics	Ingress Protection	Moisture Control	Physical Resistance	Chemical Resistance	Increase Resistivity	Key Requirements
Depth of Penetration Class 1: <10 mm Class 2: ≥10 mm	√	√	-	-	√	• To produce a water-repellent surface • No film or change in concrete appearance • Pore internally coated –not filled
Water Absorption <7.5 % Resistance to Alkali <10 %	√	√	-	-	√	
Drying Rate Class: >30 % Class 2: >10 %	√	√	-	-	√	

3.6 Impregnations or Surface Sealers

These surface treatment systems are very similar to surface coatings; however, they are designed to have a much lower viscosity, allowing them to easily penetrate the surface of the concrete (Dyer, 2014). Impregnations or surface sealing systems are subdivided into two broad categories:

1. Materials that react with the concrete to form pore-blocking products:

Materials such as silicates (sodium or potassium) and silicofluorides (magnesium or zinc) used in aqueous solutions react with the concrete's calcium hydroxide, forming an insoluble calcium salt that blocks the concrete’s outer pores. These treatments are regularly used to improve concrete floors against abrasive dusting. They are, however, ineffective when used on poor-quality concrete or concrete that has carbonated. Although they are not effective in preventing the ingress of aggressive salt solutions, they do reduce the rate of chemical attack and water penetration (Levitt et al., 1997).

2. Materials that do not react with the concrete but physically block the pores in the concrete:

The main requirement for this category is the product's ability to effectively block the pores and capillaries. The treatment relies upon sufficient solids being carried into the concrete, and as such, a balance is required between the product's viscosity and its related solids content (Levitt et al., 1997).

3.6.1 Function and mechanism

According to the protection defined in BS EN 1504-2, surface sealers that react with the concrete to form pore-blocking products effectively reduce porosity, improve the surface's physical resistance and mechanical strength, and provide protection from the ingress of aggressive agents.

Unlike hydrophobic treatments, these impregnations or surface sealers either partially or fully fill the substrate's pores, creating a discontinuous thin film on the surface of the substrate, which is likely to alter its appearance (Raupach & Büttner, 2014).

Thompson et al. (1997) describe the theories on how silicates improve the performance of concrete as follows:

1. SiO_2 precipitating in the pores;
2. Silicates form an expansive gel that fills the pores of the concrete by swelling, similar to alkali-silica reactions; and
3. Silicates react with excess calcium in the surface region to form insoluble calcium-silicate hydrates.

According to Thompson et al. (1997), equation 3.1 represents the reaction between the sodium silicate solution and the pores of the concrete. This treatment relies on the reaction between the sodium silicate and the portlandite [$Ca(OH)_2$]. It thus affirms that the reduction in the permeability of concrete is only achieved on fresh concrete or before carbonation occurs (Medeiros et al., 2012).

$$Na_2SiO_3 + yH_2O + xCa(OH)_2 \rightarrow xCaO.SiO_2\,.yH_2O + 2NaOH \qquad (3.1)$$

For sealers that do not react with concrete, a sufficient amount of solids should be carried into the concrete to effectively block the capillaries and pores. The effectiveness is dependent on the concrete’s porosity and the number of applications of the sealer. Products with a higher solids content provide less deep penetration and are only used if excessive applications will be carried out (Levitt et al., 1997).

3.6.2 Types

These sealers generally consist of organic polymers such as polyurethane, epoxies and acrylic dispersions, which do not contain pigments or fillers (Raupach & Büttner, 2014). In some instances, a curing compound is required to be added to the solution prior to the application thereof. Newer formulations have, however, been developed to ensure that the sealer is cured as soon as it comes into contact with moisture (Dyer, 2014). These products are usually applied using brushes, as shown in Figure 3-10 below. Where large horizontal areas require treatment, the site is flooded, and the impregnation is spread with a slider.

Figure 3-10: Applying the impregnation by hand (Raupach & Büttner, 2014)

The pore blocker is a product that forms due to the reaction between the compounds in the concrete and the penetrant. An example of this group is liquid silicates which react with the concrete's calcium hydroxide to form further gel products. Similarly, liquid silicofluoride reacts to form insoluble calcium silicofluoride (Mays, 2003).

Epoxy and acrylic resins are sealers that are formulated to have sufficient amounts of solids that penetrate and harden within the capillaries and pores of the substrate. These products are also considered to be pore-blockers (Mays, 2003).

For many years, the main impregnation application has been to harden the surface of concrete floors to prevent dusting and to increase the abrasion resistance of concrete roads. More recently, however, pore-blocking slurry treatments and liquid silicates have extensively been used as part of protection systems in marine environments for concrete damaged by reinforcement corrosion (Mays, 2003).

Even though the manufacturers of pore-blocking impregnations are required to provide a series of standard tests (which are further discussed below), BS EN 1504 states that the specifier should also note several requirements. There are three classes of permeability to water vapour (class 1: permeable, class 2: medium permeable and class 3: dense against water vapour). For impact loading and slip and skid resistance, there are also three classes, class 1 has the lowest resistance, while class 3 provides the highest resistance (Grantham, 2011).

3.6.3 Factors influencing performance

The factors that influence the performance of impregnations and surface sealers include the following:

a) Age and quality of concrete

Baltazar et al. (2014) found that the age and quality of the substrate did not affect the performance of silicate-based impregnations in terms of abrasion resistance and water permeability. It should be noted that the above impregnation did not increase the substrate’s impact resistance. From a durability point of view, it was noticed that the increased abrasion resistance was only observed as long as the impregnation product remained on the substrate. As expected, a lower penetration depth was observed in concrete with a lower w/c ratio, as opposed to concrete with a higher w/c ratio, stemming from the latter having higher porosity levels.

The experiments performed by Dai et al. (2010) demonstrated that the presence of cracks before or after the application of sodium silicate-based pore blockers had no impact on preventing or hindering chloride penetration and water absorption. Consequently, this treatment does not assist in preventing the initiation of reinforcement corrosion. Contrastingly, Medeiros et al. (2012) found that concrete coated with sodium silicate successfully reduced the chloride diffusion coefficient, provided that no cracks were present before or after the application. Furthermore, they emphasized that any cracks that occur after the application should be repaired immediately because the low porosity layer formed by the treatment is likely to rupture.

b) Moisture content in the surface zone

It was shown by the study performed by Baltazar et al. (2014) that the higher the moisture content of the concrete, the better the impregnation performed in terms of water permeability. The increased surface moisture content promoted the stagnation of the product, resulting in a more impermeable concrete surface. On the contrary, the high moisture content reduced the impregnation's efficacy in abrasion resistance, as the product was unable to penetrate deep and react with the concrete. The effect that the moisture content has on impact resistance was found to be marginal.

c) Surface preparation

Tests by (Levitt et al., 1997; Baltazar et al., 2014) showed that preparing the concrete surface by roughening it before applying an impregnation has no advantage in increasing its water permeability performance and only marginally improved the impact resistance, as service performance does not rely upon adhesion. Bassi & Roy (2002) however, strongly recommend that the surface be clean and free from foreign matter such as oil, grease, and dirt.

3.6.4 Performance in marine environments

Due to the high concentration of chloride ions in marine environments, chloride ions, along with water molecules, tend to penetrate the concrete surface, causing reinforcement corrosion (Li et al., 2019). Various factors that influence the performance of impregnations and surface sealers in the marine environment are discussed below. These include the effect on the transportation of chloride ions and water molecules through the concrete, the physical resistance provided and how it may extend the service life of RC structures.

a) Chloride and water transportation

Applying a surface sealer or impregnations, such as acrylic dispersions and sodium silicates, to an RC structure's surface is a practical solution for protecting RC structures in marine environments. These impregnations, as discussed below, have proven to provide substantial protection against the ingress of moisture and varying protection against the ingress of chlorides ranging from satisfactory to significant.

Results from the research carried out by Medeiros & Helene (2009) indicated that impregnations consisting of acrylic dispersions successfully inhibited water penetration. This impregnation is commonly used on RC structures in marine environments, as water can be a vehicle for chloride penetration. Evidence of the efficacy of the acrylic sealer is demonstrated by the sorptivity tests conducted by Medeiros & Helene (2009), in which the sealer reduced the sorptivity by 80 %, compared to hydrophobic agents, which only showed a reduction in sorptivity by about 70 %. However, only a 20 % reduction in the chloride diffusion coefficient was observed compared to the polyurethane surface coating, which provided an 86 % reduction in the chloride diffusion coefficient.

The results from the study performed by Medeiros et al. (2012) revealed that impregnations such as sodium silicate reduced the chloride diffusion coefficient by between 64 % and 88 % and also considerably reduced water absorption. This was only found to be true when chloride attack is the fastest degradation process, as is the case with RC structures in the marine environment, with no influence by external accidental elements.

b) Physical resistance

In harsh conditions, such as in tidal zones, added physical resistance is often required as a barrier to prevent deterioration. Aliphatic acrylic impregnations proved to be highly efficient in resisting harsh tidal zones. They aptly improved the service life of the RC structure by reducing the chloride diffusion coefficient and surface chloride content. However, these coatings typically deteriorate over time, resulting in less protection (Khanzadeh Moradllo, Shekarchi & Hoseini, 2012).

c) Concrete cover depth

According to the studies by (Medeiros & Helene, 2009; Medeiros et al., 2012), the surface sealer protection can be converted to an equivalent concrete cover depth. Results showed that acrylic and sodium silicate coatings provided a comparable additional cover depth of 50 mm and 130 mm, respectively. As increasing the concrete cover may not always be practical or in some instances aesthetically pleasing, the equivalent additional cover depth provided by the surface sealer may fundamentally change the way RC structures in marine environments are designed and maintained in the future.

d) Service life extension

Impregnations increase the service life of RC structures in marine environments. The reduced chloride diffusion coefficient extends the service life of RC structures in marine environments. In the tests done by Medeiros & Helene (2009), applying sodium silicate impregnations to an RC structure could increase its service life by an estimated 1.5 times compared to uncoated RC structures.

3.6.5 Principle performance overview

This section provides an overview of the characteristics that impregnations and surface sealers provide. Table 3-6 is reproduced using the guidelines described in (Shaw, 2009).

Table 3-6: Overview of the characteristics of impregnations and surface sealers (Shaw, 2009)

Principle Performance Characteristics	**Ingress Protection**	**Moisture Control**	**Physical Resistance**	**Chemical Resistance**	**Increase Resistivity**	**Key Requirements**
Capillary absorption and permeability to water $<0.1kg/m^2.h^{0.5}$	√	-	√	-	-	• To strengthen the surface and reduce surface porosity. • Capillaries and pores filled or partially filled • Thin-film organic polymers
Depth of Penetration ≥5 mm	√	-	√	-	-	
Adhesion strength (Pull-off Test) Average (N/mm^2) Horizontal with mechanical load: ≥1.5 Horizontal without mechanical load: ≥1.0 Vertical ≥0.8	-	-	√	-	-	
Abrasion Resistance 30 % improvement compared to the untreated sample (Taber test)	-	-	√	-	-	
Impact Resistance Class 1 ≥ 4Nm No cracks or Delamination after impact Class 2 ≥10 Nm Class 3 ≥20 Nm	-	-	√	-	-	

3.7 Overlays, Screeds or Renderings

An overlay, screed or rendering (OSR) is a thick (6mm or greater) impermeable, dense cementitious coating generally applied by a trowel or spray. Cement mortars are modified by adding polymer lattices to create a dense impermeable barrier with enhanced adhesion to the substrate (Mays, 2003).

Although these treatments are linked to surface coatings, according to Bijen (2003), overlays, screeds and renderings do not form part of the surface protection systems distinguished in BS EN 1504. They are therefore not discussed in great detail in this report.

3.7.1 Function and mechanism

OSR act as an additional protective barrier to the concrete cover against the ingress of harmful aggressive agents (Mays, 2003). They change the texture, appearance and elevation of the concrete surface. It is also used to improve drainage characteristics and applied during concrete patch repairs after deterioration has occurred (Khan & Ahmed, 2016). OSR may also be used to bridge inactive cracks, however, active cracks are likely to mirror through the treatment system (ACI Committee 546, 2014).

3.7.2 Types

OSR is usually a blend of OPC and fine-graded sand. However, more sophisticated products are designed for specific properties. These systems may also comprise special additives to control pot life and setting time, increase its waterproofing abilities, and improve thixotropy, plasticity and density (Bassi & Roy, 2002).

Polypropylene, alkaline-resistant glass and polyethylene fibres are commonly used to control cracking due to shrinkage. Although uncommon, coated carbon fibres and natural organic fibres are also used. Polymers supplied in powder or liquid form may improve cementitious coatings by increasing their physical properties, including flexibility, adhesion, water retention and plasticity (Bassi & Roy, 2002). The BS EN 1504 requires that a bonding agent be applied to the substrate before placing a polymer-modified screed (Dyer, 2014).

OSR can be divided into thin-bonded and thick-unbonded overlay systems. Thin systems require a good bond and therefore are not suitable on severely damaged surfaces as cracks tend to reflect through the thin overlay. Generally, bonded overlay systems are used on existing horizontal surfaces that are not showing significant deterioration or structural movement. In these situations, unbonded overlay systems are preferred (Tayabji & Smith, 2010; ACI Committee 546, 2014).

3.7.3 Factors influencing performance

Cement-based surface overlays should not be applied when temperatures are below 5°C or are expected to fall below 5°C within the next 24 hours after application (Bassi & Roy, 2002). Other factors that influence the performance of overlays, screeds and renderings include the following:

a) Age and quality of concrete

Cement-based overlays can last the entire design life of an RC structure if the preparation is done correctly. Many high-strength screeds require a substrate (irrespective of age) to have a cohesive strength of at least 1.5 N/mm^2. Insufficient concrete strength may lead to structural failure within the substrate due to the stresses produced during the curing of the screeds (Bassi & Roy, 2002).

b) Surface preparation

The substrate surface should be free from contaminants, including dust, dirt, oil or even previous coatings. According to Bassi & Roy (2002), previous coatings, in any condition, are more likely to act as a bond breaker rather than to assist with the adhesion of a cement-based screed. To provide good adhesion between the screed and the existing substrate, mechanically keying the surface is beneficial, as the bonding is a physical function of the smaller particles in the screed penetrating the pores.

3.7.4 Performance in marine environments

OSR may hinder chloride-induced corrosion in RC structures in marine environments. A study by Brenna et al. (2020) showed that RC structures in aggressive environments coated with a polymer-modified cementitious mortar delayed chloride-induced corrosion and reduced the corrosion rate.

Khan & Ahmed (2016) experimented with various surface treatment systems on concrete to enhance its strength and durability in harsh marine conditions. It was found that using cementitious overlays comprising multi-purpose admixtures significantly reduces water penetration into concrete and thus delays the corrosion process, providing more durable concrete. Results showed that the modified screeds performed 44 % and 55 % better than standard concrete in terms of resistance to chloride penetration and water absorption, respectively.

3.8 Unclassified Surface Treatment Systems

Newly developed surface treatment systems are often not classified in accordance with EN BS 1504 and ACI 546. Examples of these surface treatment systems are mentioned in Table 3-7 below:

Table 3-7: Unclassified newly developed surface treatment systems (Pan et al., 2017)

Surface treatment	Attributes
Silane/clay nanocomposites	This treatment system exhibits a hydrophobic effect and alters the microstructure of the concrete's cover. Studies have shown that the introduction of clay particles significantly reduces the permeability and chloride diffusion by blocking the micro-pores. In addition, the clay content lessens the surface roughness, resulting in a decreased surface area that is exposed to the environment.
Ethyl silicate	This alkoxysilane is produced through the reaction between tetrachlorosilane and alcohol. By means of the hydrolysing process, ethyl silicate forms a silica gel that fills the pore network. A two-stage reaction occurs when the ethyl silicate penetrates the pores of the substrate: 1. Ethyl silicates hydrolyses and form ethanol and silanol. 2. Silica gel precipitates inside the pore structure, as the silanol dehydrates and condenses.
Super-hydrophobic paper sludge ash	Paper sludge ash, a waste product from the paper recycling industry, can be used to create a super-hydrophobic surface treatment. Studies have shown that this treatment system has significant potential to effectively reduce water absorption and sorptivity (Wong et al., 2015).

It should be noted that although overlays, screeds and renderings were briefly discussed in this report, it too does not form part of the three classes of surface treatment systems described in EN BS 1504. Based on the literature analysed, it is clear that there is confusion regarding cementitious surface treatments. Thinner cementitious surface treatments are generally described as surface coatings while those greater than 6 mm are referred to as overlays, screeds or renderings (ACI Committee 546, 2014).

3.9 Surface Treatment Application Guidelines

Surface treatments are formulated to protect against a particular environment and achieve a long service life in that environment. The success of a surface treatment system is primarily based on its correct application.

Although concrete is inherently a suitable substrate for surface coatings, surfaces should be clean from dust, oil, mould, grease, laitance and/or any product that may affect the coating system from penetrating the substrate or affecting the bond between the coating and the concrete surface (Mays, 2003).

Silane treatments can be placed on damp concrete surfaces, although better penetration is achieved when the concrete is slightly dry, allowing the little moisture that is present in the pores for the hydrolysis reaction, which converts the silane into silicone resin (Basheer & Cleland, 2011). Pore-blocking materials and renderings, however, usually require a damp substrate.

As mentioned above, proper surface preparation is essential in ensuring the correct application of the surface treatment. According to ASTM D4258 and ASTM D4259, the most appropriate techniques for preparing a concrete surface is as follows:

- Grit blasting or water blasting – Although the use of water may cause delays, as the concrete substrate needs to dry out to a degree suitable for the intended surface treatment, these techniques are most commonly used and are incredibly effective.
- Mechanical impact – These techniques include scabbling and scarifying and are extremely effective. However, if performed too aggressively and too vigorously, they may shatter large aggregates, causing micro-cracks.
- Wire brushing – This technique is not encouraged as it is not effective.

3.9.1 Application to old concrete

RC structures in marine environments that require rehabilitation are most likely subject to reinforcement corrosion damage. It will be necessary to carry out appropriate concrete repairs before applying the selected surface treatment system. Depending on the surface treatment system and the quality of the existing substrate, it may be required to apply a fairing coat as most surface treatments will not be able to mask variations. The presence of poorly filled blow-holes and bolt-holes, protrusions and patch repairs will be difficult to disguise. In addition, surface hardeners are also required where the concrete surface is weak and friable (Levitt et al., 1997).

3.9.2 Application to new concrete

The surface of newly cast RC elements has a highly alkaline surface until carbonation occurs. The concrete will be subject to shrinkage while hydration reactions are taking place. Most surfaces will also have a film of mould-release agent and possibly a curing membrane. It is for this reason that the application of surface treatment systems is planned in advance, as this will influence the type of curing and release agents used. The factors mentioned above influence the application and selection of the surface treatment system (Levitt et al., 1997).

3.9.3 Manufacturer’s guidelines

Generally, suppliers provide guidelines that are in accordance with BS EN 1504 for the application and preparation of each surface treatment system. Although most surface treatments require concrete to cure before application, ACI 546 (2014) recommends that the manufacturers should be consulted for specific products.

Manufacturers also ensure that the products can be applied practically on-site in varying climatic conditions that may be encountered around the world. Factors such as the type of application proposed, typical coverage achieved, pot life and curing time, are commonly provided by the manufacturer. The applicator should therefore strictly follow the guidelines provided by the supplier, as various factors highlighted above influence the treatment system's effectiveness (Mays, 2003).

3.10 General Factors that Influence the Performance of Surface Treatment Systems

The protection provided by the different surface treatments varies with the substrate's condition and the type of treatment process selected (Pan et al., 2017). The following factors which affect the performance of surface treatments should be understood before treatment is specified:

3.10.1 Air permeability

Air permeability influences the performance of concrete negatively and positively. A high air permeability causes faster chloride ingress, making the reinforcement more susceptible to corrosion. Alternatively, a sufficient amount of air permeability is required to ensure breathability in the concrete to avoid damage during freezing and thawing cycles. The air permeability of surface-treated concrete can be measured by the water absorption-desorption, dry-cup/wet-cup, and Autoclam air permeability methods (Pan et al., 2017).

3.10.2 Bonding strength

For surface treatments to perform well over the long term, it requires good adhesion to the concrete substrate. Previous investigations indicated that the bonding strength of coatings should not be less than 1.4 to 1.75 MPa. The average bond strength for cementitious mortar ranges between 2.2 and 3.3 MPa, while the bond strength for epoxy coatings is about 2.9 to 4.0 MPa. Furthermore, studies have linked the substrate's surface roughness and compressive strength to the bond strength of surface treatments. The bond strength can be measured using the modified version in ASTM D4541 and ASTM C321, as shown in Figure 3-11 (Pan et al., 2017).

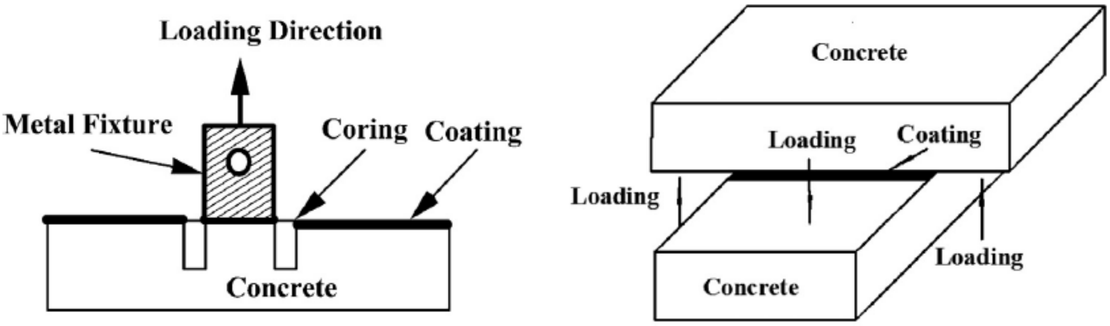


Figure 3-11: (a) ASTM D 4541; (b) ASTM C 321 (Pan et al., 2017)

3.10.3 Coating thickness and penetration depth

Impregnation agents should penetrate as deeply as possible into the concrete substrate to ensure its long-term durability. Pan et al. (2017) note that impregnation penetration depth cannot be easily measured. The penetration depth of the surface treatment agent depends on a range of factors such as:

- The surface treatment properties, mainly viscosity and molecular size;
- The solvent type;
- The saturation and porosity of the concrete substrate;

- The reaction time; and
- The rate of the reaction – water-repellent film formed by the silane.

The thickness of surface coatings is negligible, and the penetration depth has minimal impact on its protection. The thickness of the surface coating can be measured either directly or by utilizing a mobile nuclear magnetic resonance (NMR) instrument (Pan et al., 2017).

3.10.4 Cracking resistance

Concrete easily cracks due to its relatively low tensile strength. Therefore, the applied surface treatment should have adequate cracking resistance or crack healing ability. Pan et al. (2017) have shown that silane treatment and polymer coatings may protect concrete with cracks up to 0.06 mm wide.

There are currently two popular methods of measuring the crack-bridging ability of surface coatings, namely:

1. **To measure the ability to bridge a crack indirectly by measuring the creep of coatings**
   Under this method, strips of coatings are placed in two jaws and a constant stress of 0.5 MPa is applied; and

2. **The direct crack-bridging test**
   Forces are added to a concrete sample to ensure the crack is developed at about 0.5 mm/min. The slab initially cracks due to an increase in stress. The stress then rapidly decreases, representing the coating's crack-bridging ability as depicted in
   Figure ***3-12***.

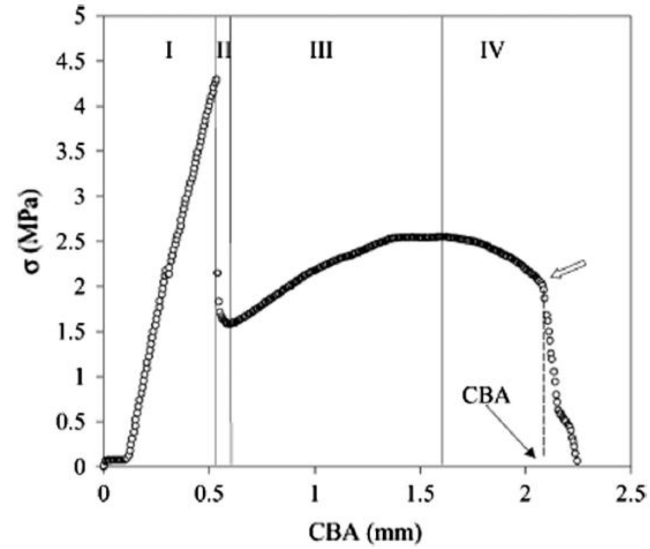


Figure 3-12: Stresses of concrete and surface coating during a crack-bridging ability test (Pan et al., 2017)

3.11 Service Life of Surface Treatment Systems in Marine Environments

As previously discussed, evidence from numerous studies has proved that the application of surface treatments significantly increases the service life of RC structures. However, surface treatment systems lose their positive impact on service life promotion once their performance against chloride penetration is lost (Khanzadeh Moradllo, Shekarchi & Hoseini, 2012). This chapter discusses the durability and long-term (at least ten years of service) residual protection of these systems and the effect that the exposure conditions have thereon.

3.11.1 Effect of exposure conditions

Literature showed that the long-term performance of surface treatment systems is affected by the imperfections of the surface, surface preparation, cyclic wetting and drying, the skill of the applicator and the environmental conditions at the time of the application (Christodoulou et al., 2013). Surface treatment systems are also more vulnerable to deterioration in severe marine environments. Khanzadeh Moradllo, Shekarchi & Hoseini (2012) studied the long-term performance of surface coatings in tidal exposure conditions and ascertained that surface coatings deteriorated significantly faster in these harsh conditions than in other marine environments.

In tests conducted by Khanzadeh Moradllo, Shekarchi & Hoseini (2012), it is clear that the performance of surface treatments in tidal zones is time-dependent and does not provide long-term protection. Their study concluded that applying suitable quality surface treatments witnessed a noticeable improvement in reducing chloride concentration. This improvement, however, decreased with time and provided very little protection after 50 months of exposure.

The tests by Sadati, Arezoumandi & Shekarchi (2015) show that the surface treatments still provided protection at 88 months of soil exposure to high chloride concentrations. The authors attribute this to the surrounding soil, which most likely protects the surface treatment against weathering effects such as UV.

Mcauliffe (2019) predicts that in non-trafficable surfaces, silane/siloxane systems with a low-solids system have a lifespan of 10-15 years, while silanes with a high-concentration two-coat system can last as long as 20-30 years. However, deep penetrating silanes are predicted to only last between 8-12 years on bridge decks and other high-traffic surfaces, as the surface treatment erodes much faster.

3.11.2 Surface treatment lifespans

A study from Christodoulou et al. (2013) provides clear evidence that hydrophobic impregnations continue to protect RC structures in marine environments even 20 years after application, albeit to a lesser degree than recently coated surfaces. This shows that there is a clear relationship between the degradation of impregnation and the provided protection.

Experiments have shown that polyurethane coatings may protect the RC structure from corrosion damage for 11-30 years, while epoxy coatings are effective for 3-8 years. Moreover, the time taken for corrosion initiation when applying an acrylic coating is 6-10 years (Almusallam et al., 2003).

As expected, polyurethane coatings provide the best protection for RC structures in marine environments regardless of the severity of the environment. However, the severity of the condition influences the duration of the protection regardless of which surface treatment is used.

The investigation by Sadati, Arezoumandi & Shekarchi (2015) depicted results testing various surface treatments in which an increase in chloride ion concentration in coated specimens was observed throughout the exposure time. This suggested that chloride ion diffusion into concrete is a time-dependent phenomenon and most surface treatment systems lose their efficacy with time.

According to Khanzadeh Moradllo, Shekarchi & Hoseini (2012), Bertolini et al. (2013), and the service life prediction model by Violetta (2002), surface treatment systems have time-dependent performance and will lose their protective influence on the service life of RC structures as time passes. Surface treatment systems should be reapplied to the RC structure before their default deterioration time (Sadati, Arezoumandi & Shekarchi, 2015). Furthermore, it is mentioned that due to the durability of the protection systems being far lower than that of the concrete, regular maintenance should be scheduled (de Medeiros et al., 2016).

3.12 Summary of the Various Treatment Systems

Table 3-8 below summarises the different surface treatment systems discussed in detail in this report, including the different types within a particular treatment system, the reason one would consider applying these systems, and a summary of the benefits and shortfalls thereof. It may aid engineers and practitioners in selecting the correct treatment system for projects in marine environments.

Table 3-8: Surface Treatment Summary

Treatment System	Types	Reason for treatment	Comments
Surface Coating	Organic Inorganic	• Protection against ingress • Moisture control • Increase physical, mechanical and chemical resistance • Increasing resistivity • Cathodic control	Cost-effective method to protect RC structures in marine environments. Successfully inhibits water penetration, thus reducing chloride penetration. It may reduce the chloride diffusion coefficient by up to 86 %. Cementitious coatings create an effective physical barrier to protect the substrate from wet-to-dry cyclic conditions. Studies have shown that these coatings can increase the service life of RC structures in marine environments by up to 7.8 times. Most studies have shown that polyurethane coatings provide the best protection for RC structures in marine environments.
Hydrophobic Impregnation	Silanes Siloxanes	• Moisture control	While no physical barrier is created, hydrophobic impregnations significantly reduce water uptake and dissolve aggressive agents. Hydrophobic impregnations enhance the service life of RC structures in marine environments by up to 4 times. Silanes offered good chloride ion resistance. Improvements by up to 50 % were found when using silane compounds gel.
Impregnations and Surface Sealers	Reacts with concrete Does not react with concrete	• Protection against ingress • Physical resistance • Chemical resistance	Significantly extends the service life of RC structures in marine environments. Results indicated that impregnation coatings successfully inhibited water penetration by reducing the sorptivity by 80 %. In addition, a 20 % reduction in the chloride diffusion coefficient was observed.
Screeds and Overlays	Cementitious coatings	• Physical resistance • Chemical resistance	Effectively delays chloride-induced corrosion and reduces corrosion rate in RC structures in marine environments. Results showed that modified screeds performed 44 % and 55 % better than that standard concrete in terms of resistance to chloride penetration and water absorption, respectively.

4. Availability of Standards for Surface Treatments

4.1 Introduction

In addition to the already known deterioration causes (physical, mechanical, biological and chemical), as well as human failures (inadequate use of materials, project flaws, failures during construction and non-existence of maintenance), other factors have led to unsatisfactory construction. This includes fierce competition that places contractors under pressure, which may lead to the construction of an inferior product. As a result, ageing RC structures laden with anomalies require preservation techniques and methods (Monteiro, Trautwein & Almeida, 2017).

Standards and guidelines are therefore necessary for the construction industry, as they ensure that the contractor overseeing the construction is protected, as well as ensuring that the required quality is achieved. Test methods and specifications also guarantee that a contractor has control over the construction work and that the work completed can be adequately assessed and proper accountability is established (Smuts, 2015).

4.2 European Standards

Significant changes are underway, with amendments being made to the construction standards, design codes, test methods and material specifications for concrete. All European countries, including the UK, are required to adopt the European standards issued by the European Committee for Standardisation (CEN). Consequently, South Africa, which previously based its standards on that of the UK, is also forced to amend its concrete codes, specifications and test methods to align with the EN standards (Smuts, 2015). The standard used for the repair and protection of RC structures, which most of the surface treatments sold worldwide abide by, is the BS EN 1504 series (Bamforth, 2004).

Smuts (2015) further explain that the European standards philosophy includes determining the longevity of the structure and also the required durability thereof in a specific environment. The philosophy also requires that an appropriate approach to achieve this durability is determined at the outset and only then shifting the focus to the structural design of a building.

As existing infrastructure is increasingly ageing, the need for repair and protection is rapidly growing. The substantial development of new materials and methods for the repair and protection of RC structures has led to the need for standards such as BS EN 1504 (Raupach & Büttner, 2014). BS EN 1504 is based on previous work on repair strategies published in Europe, including the RILEM Technical Committees, reports written by the UK's Building Research Development, German guidelines on repair, and other reports from various concrete societies (Grantham, 2011). Within BS EN 1504 Part 2, several standards characterise surface treatment systems, many of which govern the factory control systems – ensuring that the products are manufactured consistently in terms of identification and performance (Grantham, 2011). Quality

Control and testing that can be carried out on-site are covered in BS EN1504-10 (Grantham, 2011).

BS EN 1504 comprises a 10-part series of main standards and 61 standards for test methods. The structure of the series is depicted in Figure 4-1.

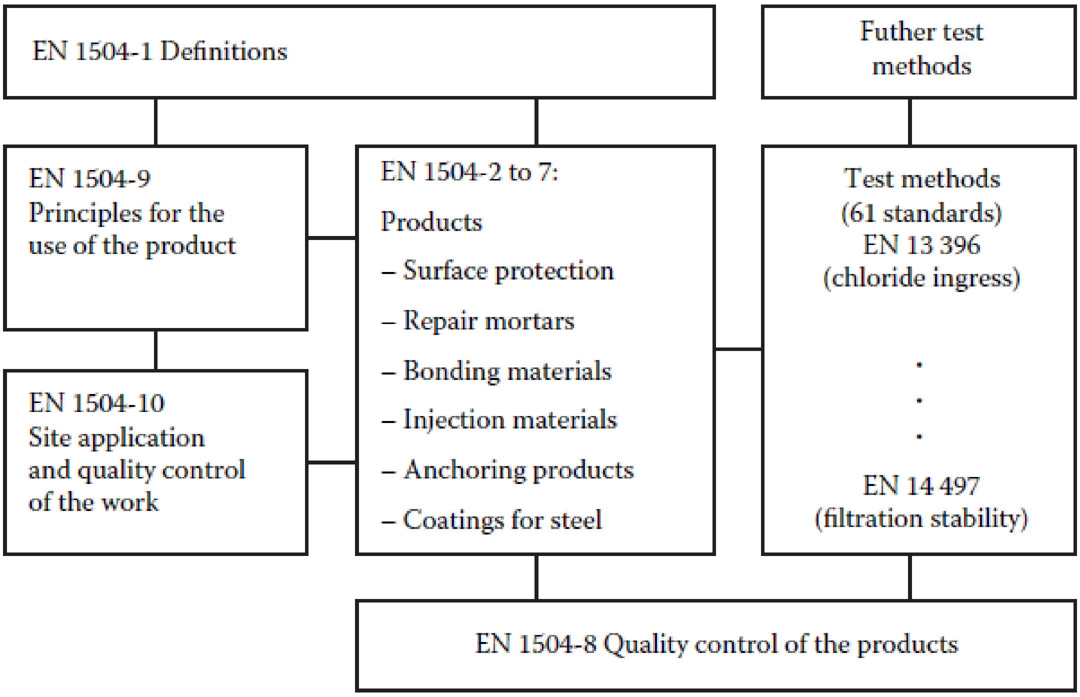


Figure 4-1: The structure of the series of BS EN 1504-1 to BS EN 1504-10 (Raupach & Büttner, 2014)

BS EN 1504 defines different principles for repair and protection of damages to the concrete (Principles 1-6) and protection against reinforcement corrosion (Principles 7-11), as shown in Table 4-1 below (reproduced from BS EN 1504). These principles have been established from the RILEM Technical Recommendation 124-SRC, “Strategies for the repair of concrete structures damaged by steel corrosion” (Raupach & Büttner, 2014).

The principles and short descriptions of the methods of protection that are relevant to this study are described in Table 4-2 (reproduced from BS EN 1504) and briefly discussed below.

4.2.1 Moisture control

Moisture control is the ability of the surface treatment to inhibit the flow of liquid into the concrete while still allowing the concrete to ‘breathe’. Surface treatments customarily were designed to seal the surface entirely. However, it has proven to be beneficial to allow water vapour to exit via the concrete surface. The most commonly used treatments that delay or prevent water ingress while still allowing the transfer of vapour across the surface of the concrete are silanes, pore-liners and siloxanes (Basheer & Cleland, 2011).

BS EN 1504-9 suggests that soffits and vertical surfaces should be permeable to water vapour, but upper horizontal surfaces need not be. The standard also allows for a test that classifies whether the formulation is impermeable or permeable.

4.2.2 Protection from ingress

‘Protection from ingress’ refers to the prevention of movement from harmful substances to either the steel reinforcement or the concrete. These include carbon dioxide, chloride ions and water (Dyer, 2014).

4.2.3 Increasing physical resistance

Coatings aim to increase the physical resistance of the concrete surface, in particular, to protect against abrasion, impact and freeze-thaw attack.

4.2.4 Increasing resistivity

Increasing resistivity refers to reducing the concrete’s electrical conduction by decreasing its moisture levels during service. By reducing the electrical conduction, the reinforcement corrosion process is slowed considerably.

4.2.5 Resistance to chemicals

Chemical resistance refers to the concrete’s resistance to acid and sulphate attacks. According to BS EN 1504, surface treatment systems should address at least one or all of the abovementioned principles. To establish effectiveness, surface treatments are measured against ‘compulsory performance requirement’ tests. Irrespective of the surface treatment’s primary purpose, it is compulsory to meet the requirements concerning capillary absorption, adhesion strength and liquid water permeability.

It should be noted that conformance to BS EN 1504-2 does not guarantee that the surface treatment system will provide the necessary level of protection. However, a properly designed and applied system has the best chance of attaining the required result (Grantham, 2011).

Table 4-1: Repair Principles based on BS EN 1504-9 (Raupach & Büttner, 2014)

Principles for Repair and Protection for damages to the concrete		Principles for Protection against reinforcement corrosion	
Principle No.	**Principle and its Definition**	**Principle No.**	**Principle and its Definition**
Principle 1 (PI)	Protection against Ingress	Principle 7 (RP)	Preserving or Restoring Passivity
Principle 2 (MC)	Moisture Control	Principle 8 (IR)	Increasing resistivity
Principle 3 (CR)	Concrete Restoration	Principle 9 (CC)	Cathodic Control
Principle 4 (SS)	Structural Strengthening	Principle 10 (CP)	Cathodic Protection
Principle 5 (PR)	Physical Resistance	Principle 11 (CA)	Control of Anodic areas
Principle 6 (RC)	Resistance to Chemicals		

Table 4-2: Principles and Methods of Protection (Raupach & Büttner, 2014) **&** (Grantham, 2011)

Principles for Repair and Protection for damages to the concrete		
Principle No.	**Principle and its Definition**	**Methods Based on the Principle**
Principle 1 (PI)	Protection against Ingress (Preventing or reducing the ingress of harmful agents such as water, vapour, chemicals and biological agents)	Hydrophobic impregnation Impregnation Coatings
Principle 2 (MC)	Moisture Control (Adjusting and maintaining the concrete’s moisture content to be within the specified range of values)	Hydrophobic impregnation Impregnation Coatings
Principle 3 (CR)	Concrete Restoration (Restoring a structure to its original shape and function	Overlays and screeds
Principle 5 (PR)	Physical Resistance (Increasing resistance to mechanical and physical attack)	Impregnation Coatings Overlays and screeds
Principle 6 (RC)	Resistance to Chemicals (Increasing the concrete’s surface resistance to deterioration by chemical attack)	Impregnation Coatings Overlays and screeds
Principles for Protection against reinforcement corrosion		
Principle No.	**Principle and its Definition**	**Methods Based on the Principle**
Principle 8 (IR)	Increasing resistivity (Increasing the concrete’s electrical resistivity)	Hydrophobic impregnation Impregnation Coatings

4.3 ACI and ASTM Standards

The American Concrete Institute ACI 515.2R-13 - Guide to Selecting Protective Treatments for Concrete and ACI 546.3R-14 - Guide to Materials Selection for Concrete Repair provides extensive literature on the use of concrete surface treatments. Although not often used in South Africa, these standards offer a useful reference when considering different surface treatment systems while also including relevant ASTM testing methods (ACI Committee 546, 2014). Detailed guidelines on selecting a suitable treatment for the protection of concrete against a specific substance and its effect on the concrete are presented in tables in ACI 515.2R-13 (ACI Committee 515, 2013).

4.4 International Organization for Standardization

The subcommittee is currently developing standards and guidelines for applying protective surface treatments to concrete substrates. ISO/TC 35/SC 15 – Protective Coatings: Concrete surface preparation and coating application intend to cover all aspects of coating applications. It aims to include testing for contaminants on/in the concrete substrate, surface preparation methods and materials, coatings application methods, and inspection techniques once coatings have been applied.

4.5 Summary of the Available Standards

Table 4-3 below summarises the different available standards for surface treatment systems discussed in this report.

Table 4-3: Summary of Available Standards

Standards	Comments
European Standards	All European countries, the UK and South Africa are required to adopt the European standards issued by the European Committee for Standardisation. The BS EN 1504 series are the standards used for the repair and protection of RC structures, to which most of the surface treatments sold worldwide conform to. This series of standards is based on previous work on repair strategies published in Europe, including the RILEM Technical Committees, reports written by the UK's Building Research Development, German guidelines on repair, and other reports from various concrete societies. BS EN 1504 comprises a 10-part series of main standards and 61 standards for test methods.
ACI and ASTM Standards	These standards are a useful reference when considering different surface treatment systems. They also include relevant ASTM testing methods. The tables presented in ACI 515.2R-13 provide detailed guidelines on selecting suitable treatment systems for the protection of concrete against specific substances and their effect on the concrete.
International Organisation for Standardization	The subcommittee is in the process of developing standards and guidelines for applying protective surface treatments to concrete substrates in various environments.

5. Conclusion and Recommendations

Concrete is strong, durable, versatile and economical, making it the ideal building material for RC infrastructure worldwide. For this reason, many prominent buildings and bridges were built using reinforced concrete. However, numerous renowned RC infrastructures have experienced unexpected premature deterioration over the last few decades.

Several countries rely on RC infrastructure for economic and social reasons. In South Africa, many structures are reaching their designed service life; however, given the lack of finances, it is implausible that these structures will be decommissioned and rebuilt. As a result, there is a need to maintain and prolong existing RC structures' service life and ensure that all new structures last as long as possible.

The predominant cause of premature deterioration of RC structures in the marine environment is the corrosion of the steel reinforcement caused by chloride ingress. This dissertation has shown that surface treatment systems may be used to improve the durability of new RC structures and rehabilitate deteriorated infrastructure in marine environments. Furthermore, surface treatment systems can potentially increase the service life of these structures.

This dissertation analysed and recognised the positive effect that surface treatment systems have on the durability of RC structures in marine environments with reference to previous laboratory and in-situ literature thereon. Furthermore, it appraised various international standards and the status of current specifications.

Surface Treatment Systems

The types and mechanisms and factors affecting the performance of the different surface treatment systems were discussed in detail in this dissertation. Furthermore, the application guidelines were deliberated and it was evident that the application method directly influenced the performance of the selected surface treatment.

From the research, it is apparent that design engineers working in marine environments should have a clear understanding of the various available surface treatment systems and their benefits and shortfalls.

Surface treatment systems for RC structures in the marine environment can be divided into four categories: surface coatings, hydrophobic impregnations, impregnations or surface sealers, and screeds and overlays.

Surface Coatings

Surface coatings create a pinhole-free film over the surface of the concrete that acts as a barrier to prevent the passage of moisture or corrosive substances from penetrating the cementitious substrate.

It is a cost-effective method to protect RC structures in marine environments and successfully inhibits water penetration, thus reducing chloride penetration. It may reduce the chloride diffusion coefficient by up to 86 %. Polyurethane coatings have provided substantial protection for RC structures in marine environments. Studies have shown that these coatings can increase the service life of RC structures in marine environments by up to 7.8 times compared to untreated concrete. It should be noted that large performance differences were sometimes noticed for the same generic polyurethane from different suppliers.

Hydrophobic Impregnation

As discovered in this dissertation, hydrophobic impregnations render the concrete surface hydrophobic by lining the concrete's pores and repelling moisture. The effect on the concrete surface is minimal, as no physical barrier is created on the concrete surface, thus still allowing it to 'breathe'. This is one of the reasons the use of hydrophobic impregnations is very popular. Hydrophobic impregnation causes the water droplets in contact with the surface of the concrete to form a large contact angle, thereby limiting the extent to which the water can enter the concrete pores.

Hydrophobic impregnations notably reduce the uptake of water and dissolved aggressive agents. In the early stages of marine exposure, it resists chloride ions effectively, but the protective effect steadily declines as the marine exposure time increases. However, treatments as old as 20 years may still be present and may continue to offer a residual protective effect.

Furthermore, hydrophobic impregnations may enhance the service life of RC structures in marine environments by up to 4 times compared to untreated concrete.

Impregnation or Surface Sealers

These sealers are designed to have a much lower viscosity than surface coatings and can therefore penetrate the surface of the concrete. Impregnations proved to be highly efficient in resisting the effects of harsh marine environments such as tidal sea zones. They aptly improved the service life of the RC structure by reducing the chloride diffusion coefficient and surface chloride content. Results indicate that impregnation coatings successfully inhibit water penetration by reducing the sorptivity by 80 %. In addition, a 20 % reduction in the chloride diffusion coefficient was observed.

Screeds and Overlays

An overlay or screed is a thick impermeable, dense cementitious coating generally applied by a trowel or spray. Coated with a polymer-modified cementitious mortar, RC structures in aggressive environments delayed chloride-induced corrosion. It was found that using cementitious systems comprising multi-purpose admixtures significantly reduces water penetration into concrete and thus delays the corrosion process. Results also showed that modified screeds perform 44 % and 55 % better than standard concrete in terms of resistance to chloride penetration and water absorption, respectively.

Available Standards for Surface Treatment Systems

International standards and codes of practice on surface treatment systems were investigated in this dissertation. The countries in Europe, including the UK, are required to adopt the European standards issued by the European Committee for Standardisation (CEN). As South Africa does not have any standalone standards, it must amend its concrete codes, specifications and test methods to align with European standards.

This dissertation further explains that the new European standards philosophy includes determining the longevity of the structure and also the required durability thereof in a specific environment, such as marine environments. The philosophy also requires that an appropriate approach to achieve this durability is determined at the outset. The standard used for the repair and protection of RC structures, which most of the surface treatments sold worldwide abide by, is the BS EN 1504 series.

Analysis and Recommendations

This research study has shown that the performance of surface treatment systems is a complex issue which involves various physical-chemical mechanisms. It is, however, evident that surface treatment systems can prevent the ingress of aggressive substances such as chloride ingress in marine environments and as such extend the service life of new and existing RC structures.

Polyurethane surface coatings and hydrophobic impregnations seem to be the most popular treatment systems. While all surface treatment systems presented in this dissertation reduced capillary water absorption, the most efficient surface protection treatment system reduced the chloride diffusion coefficient on concrete by as much as 86 %.

The performance of surface treatment systems was found to be largely affected by bond strength, penetration depth, substrate properties and the application method. Therefore, the preparation of the substrate surface is essential for any surface treatment to perform effectively.

As expected, the BS EN 1504 series for the repair and protection of RC structures currently provides the most comprehensive surface treatment systems guidelines. Further research is currently being carried out by ISO and will hopefully provide new and improved guidelines to aid engineers and practitioners in their selection and application.

This study demonstrated that the use of surface treatment systems is without a doubt an effective way of protecting RC structures in marine environments. Notwithstanding the above, further investigations are required, including (but not limited to) the following:

- A cost-to-performance duration study should be conducted to determine the feasibility of each treatment system.
- Whether varying ocean salinity concentrations, temperature and humidity conditions affect the performance of surface treatment systems.
- The performance of duel treatment systems, such as water repellents and acrylics were excluded in this study but may provide successful results and should be further investigated.
- Design engineers and practitioners in South Africa should insist that the products used by contractors conform to the guidelines provided by the BS EN 1504 series. This approach may be revisited at such time when ISO develops its guidelines for protective surface treatment systems for RC structures in marine environments.

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